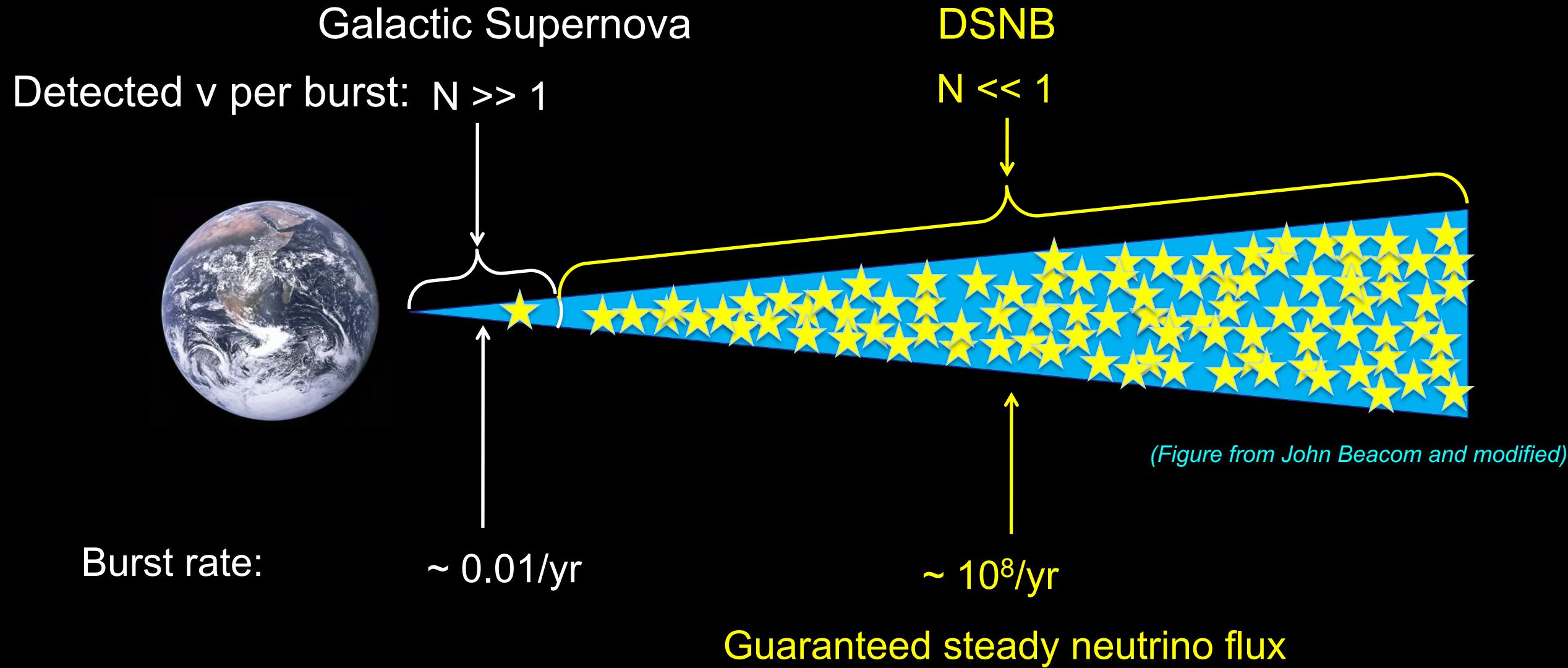


Low-energy atmospheric neutrinos and DSNB in Super-Kamiokande

Bei Zhou
(With Prof. John Beacom)
CCAPP, The Ohio State University

Fermilab, Batavia, IL

Diffuse Supernova Neutrino Background (DSNB)



What Determines the DSNB Flux

$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^\infty [(1+z)\varphi[E_\nu(1+z)]][R_{SN}(z)] \left[\left| \frac{c dt}{dz} \right| dz \right]$$

DSNB flux
($\sim 10 \text{ cm}^{-2}\text{s}^{-1}$)

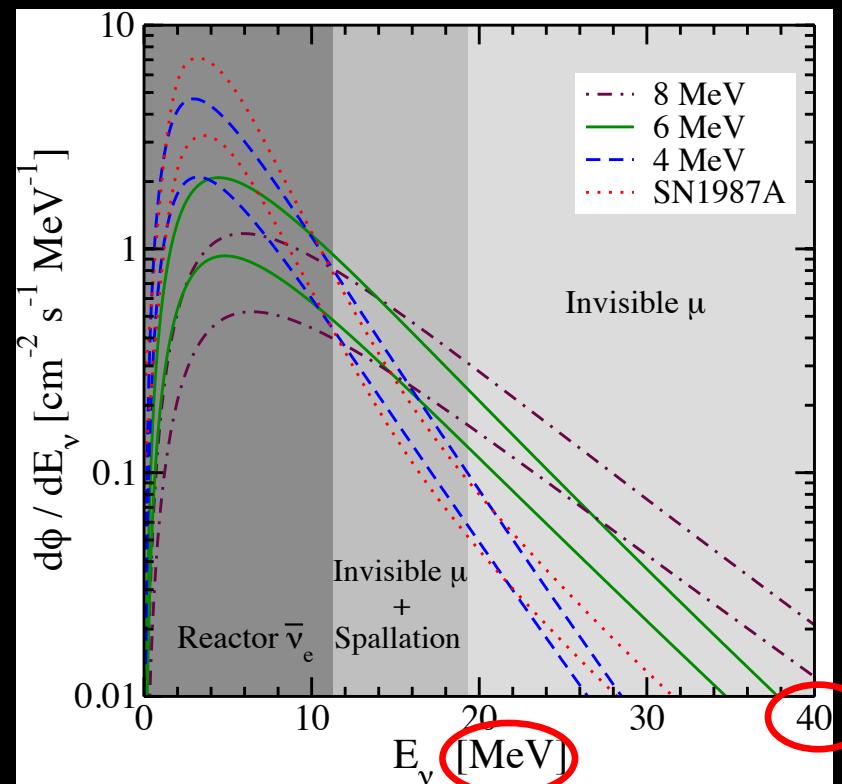
ν spectrum per supernova
(Not very well known)

(Beacom, Ann.Rev.Nucl.Part.Sci. 2010)

Cosmic supernova rate
(Relatively well known)

Properties:

- All ν flavor
- Steady
- Isotropic
- Averaged ν fluxes of supernovae



Different DSNB flux

Horiuchi, Beacom, Dwek, PRD 2009

Diffuse Supernova Neutrino Background (DSNB)

~~Background~~

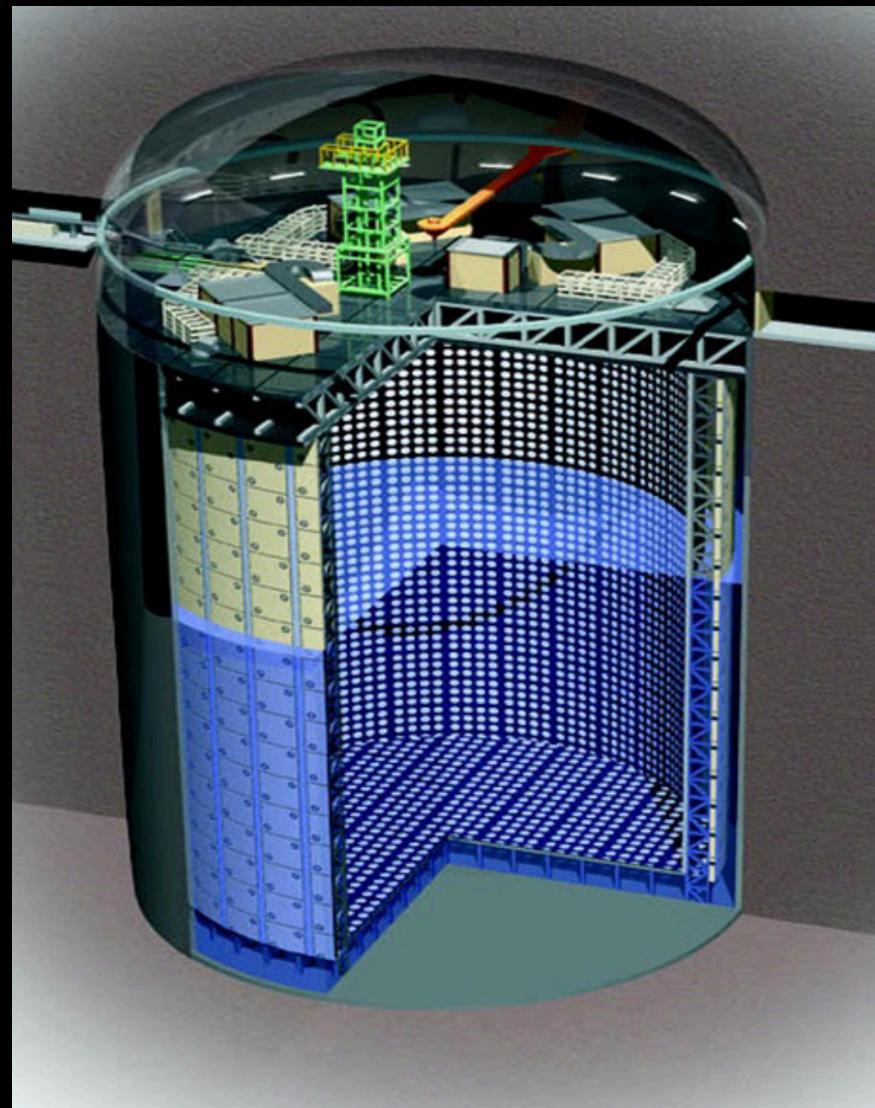
Signal

Why detecting DSNB is so important?

- (Almost) Same physics as galactic supernova ν
 - i. SN physics (unreachable by photons)
(explosion mechanism, ν mixing)
 - ii. Particle physics
(electric dipole/magnetic moment, BSM involving ν's)
- More than galactic supernova ν
(Cosmic rate of dark collapses, core collapses, and star formation)
- Fourth extraterrestrial ν source (cf. the Sun, SN1987A, IceCube)
 - Pushing neutrino frontiers to **cosmic distance**

DSNB Detection

- Super-Kamiokande (SK)
(Water Cherenkov Detector)
- Detection process
 $\bar{\nu}_e + p \rightarrow n + e^+$ (Inverse Beta Decay)
- ~ 5 events/yr (theory prediction)
So ~ 100 events collected so far,
but not identified.
(Hyper-Kamiokande will be ~ 50 events/yr)



(Figure from SK website)

Large Backgrounds

- **Atm. $\nu_\mu/\bar{\nu}_\mu$ (Dominant)**

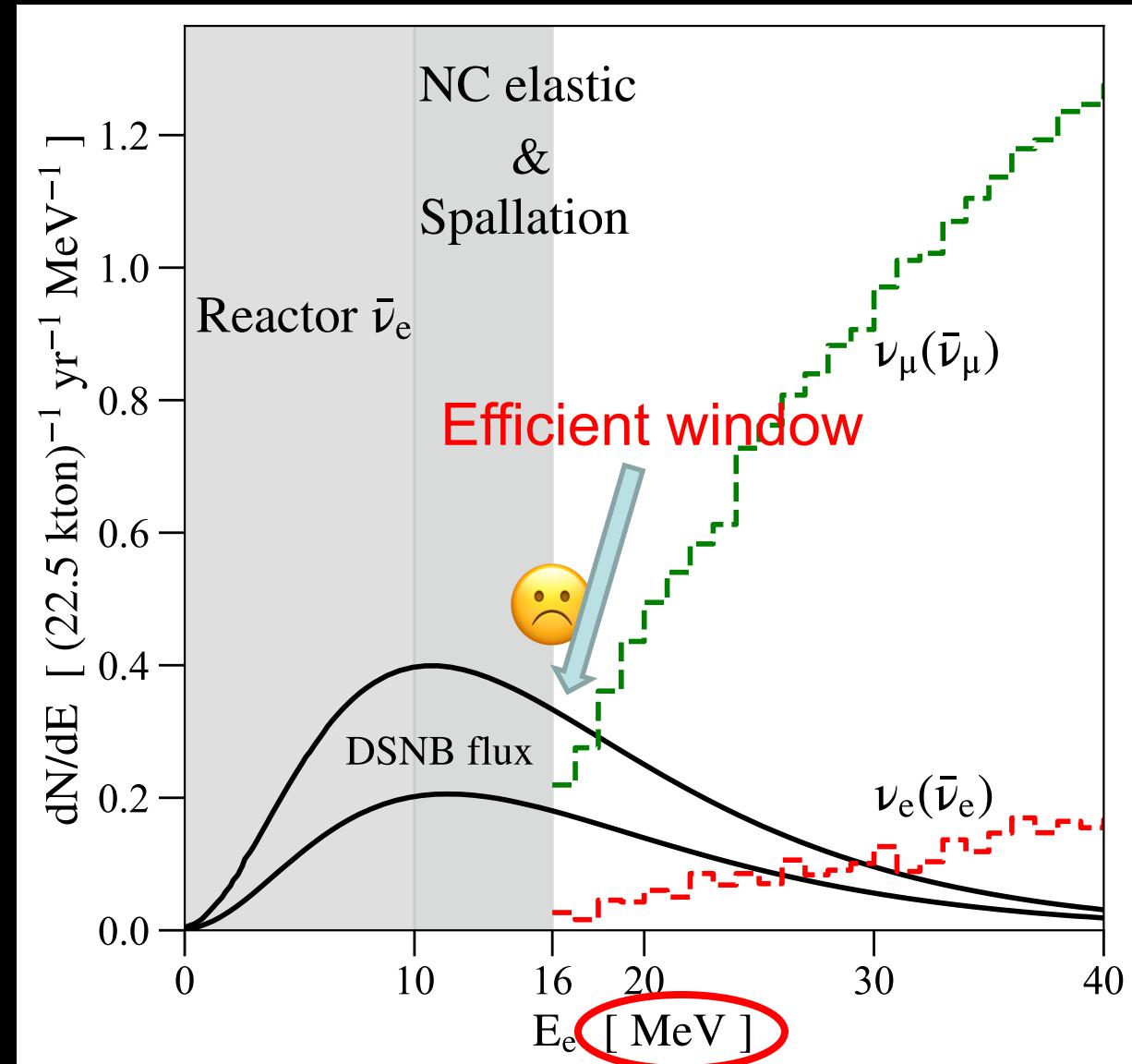
$\nu_\mu(\bar{\nu}_\mu) + \text{H}/\text{O} \rightarrow \text{X} + \mu^-(\mu^+)$, etc.

$K_\mu < 55 \text{ MeV}$, invisible

μ decay to e , mimic DSNB events

- **Atm. $\nu_e/\bar{\nu}_e$ CC**

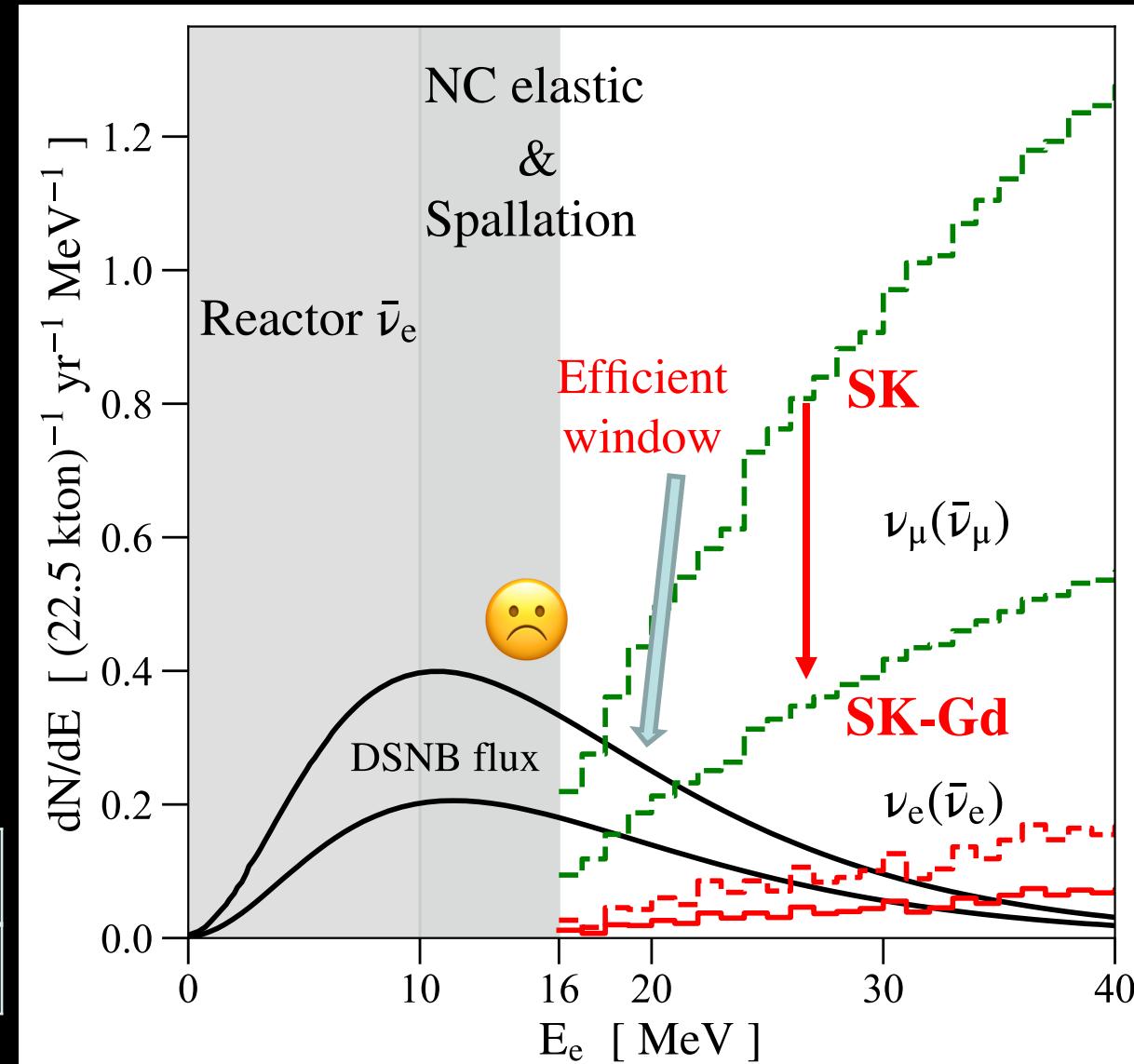
$\nu_e(\bar{\nu}_e) + \text{H}/\text{O} \rightarrow \text{X} + e^-(e^+)$



SK-Gd, New Era of DSNB Detection

- Add Gd (Gadolinium) to SK water
(Beacom & Vagins, PRL 2004, hep-ph/0309300)
- Enable SK to detect neutrons (multiplicity, etc.)
(neutron tagging)
- SK → SK-Gd, begins soon!!
- Improve DSNB detectability

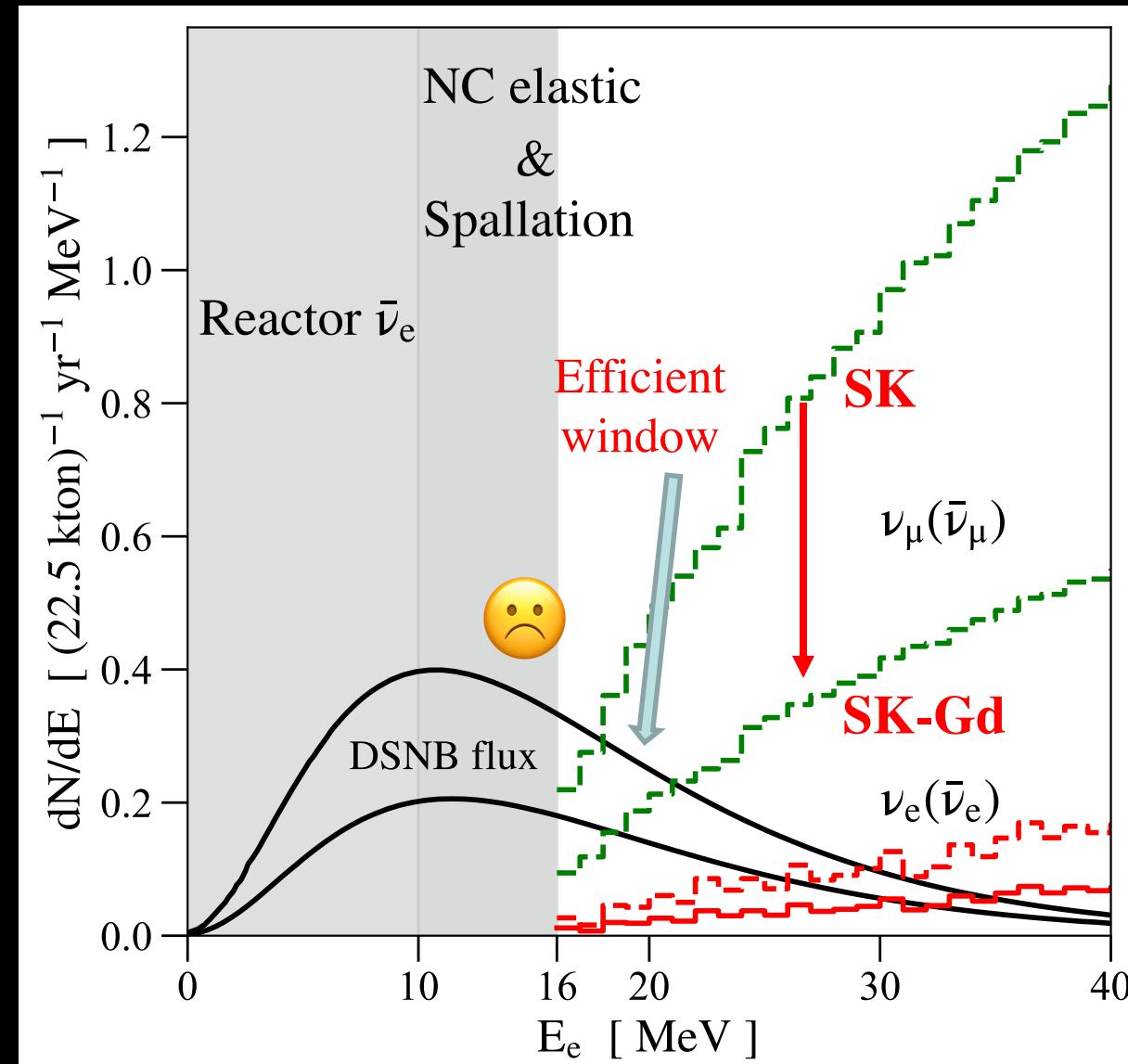
DSNB	Atm. ν bkgd.
100% one neutron	$\sim 50\%$ one neutron



Goal of Our Work:
further reduce the one-neutron atm. ν bkgd

Goal of Our Work: further reduce the atm. v bkgd.

- Study the underlying physics
 - (Atm.) ν interactions-nucleus (water) interactions.
 - Propagations/Interactions of secondaries ($\pi/\mu/\text{neutron/proton}$)
(No systematic study before)
- Find ways to further reduce them

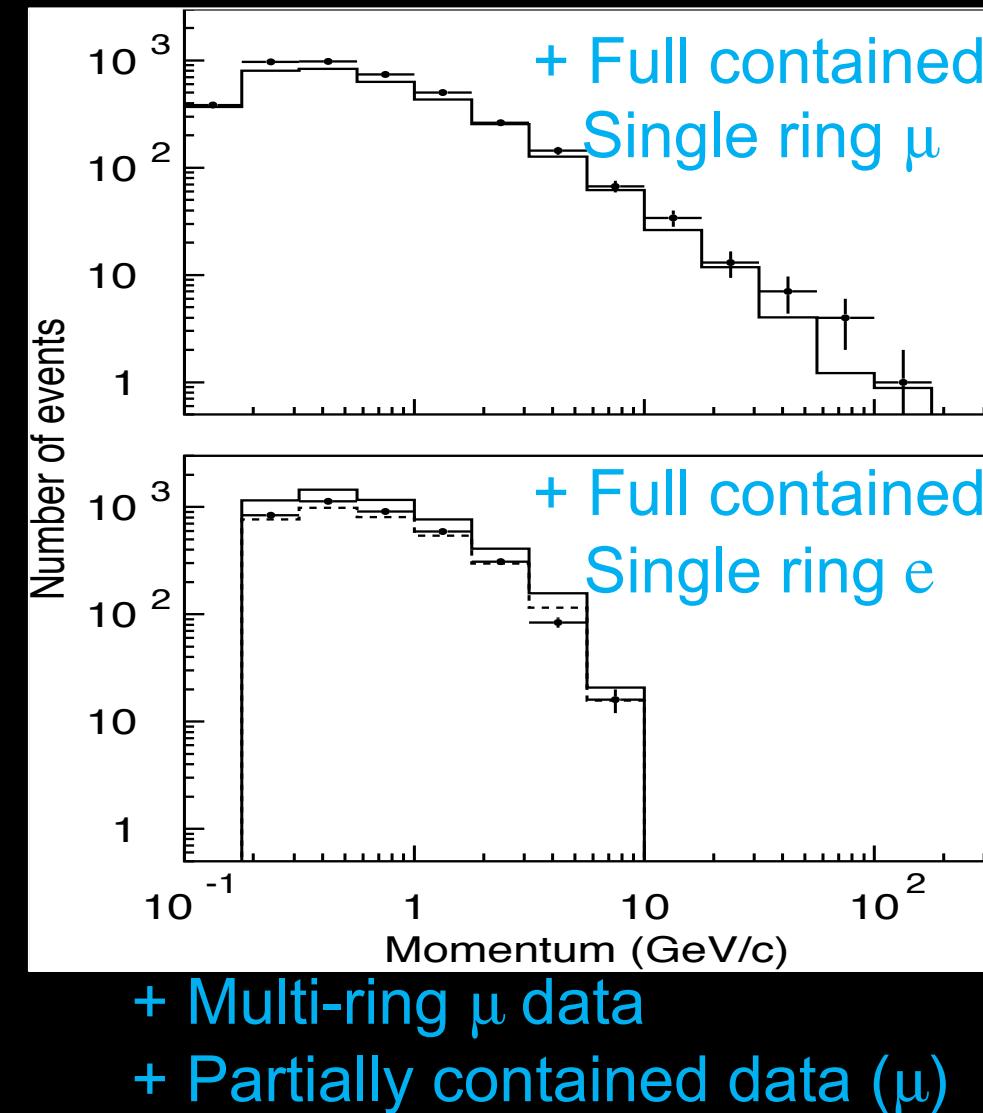


Part 1: study the underlying physics of LE atm. ν in Super-K

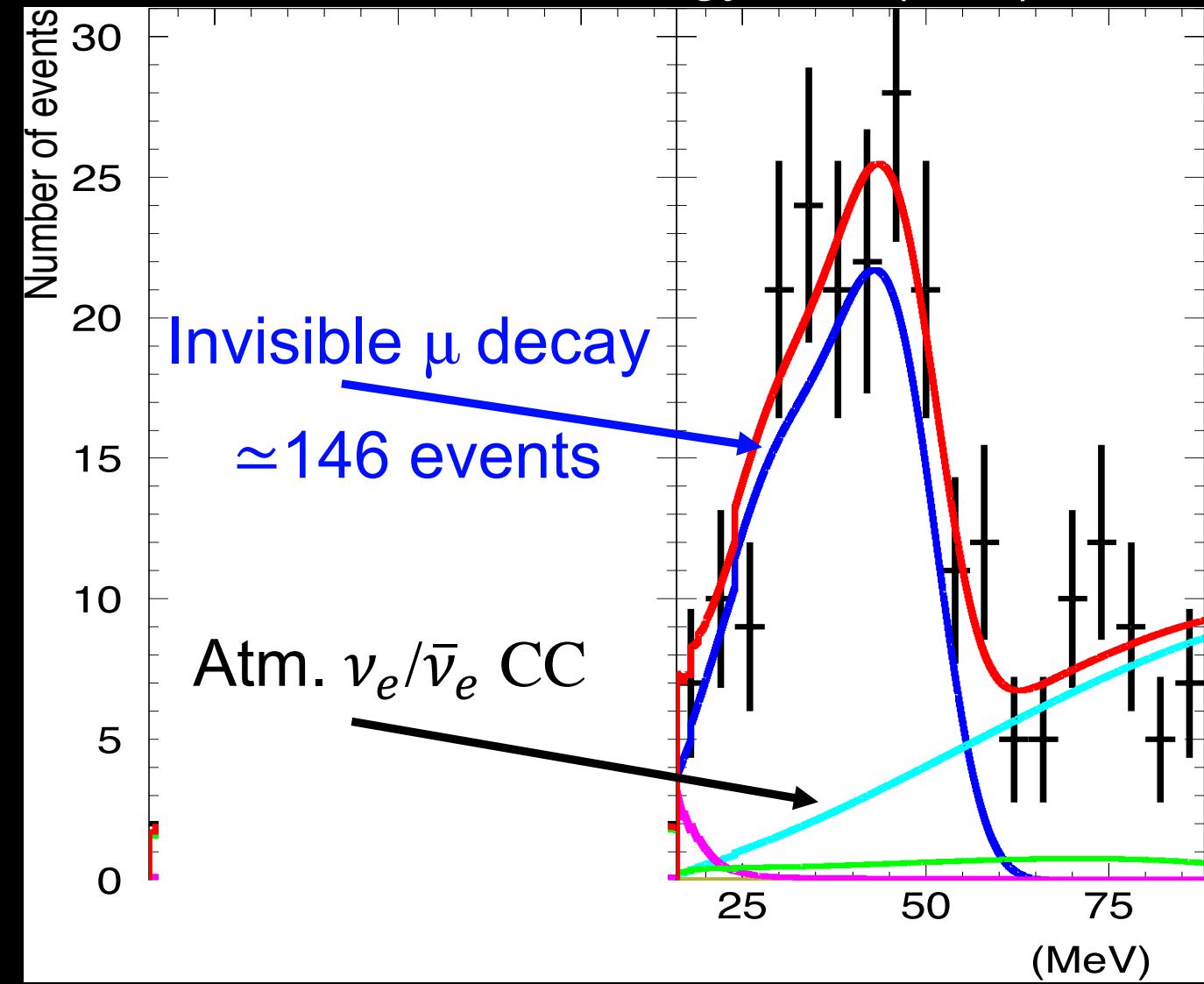
Guidance: reproduce Super-K's atmospheric ν data

Super-K's atmospheric neutrino data

High-energy data (SK-I)



Low-energy data (SK-I)



Basic Calculational framework

Detector exposure (~ 1500 days for SK-I)

$$\frac{dN_f}{dp_f} = \Delta t \sum_{\nu T \rightarrow f} N_T \int dE_\nu \frac{d\Phi}{dE_\nu}(E_\nu) P_{osc}(E_\nu, \theta_z) \frac{d\sigma_{\nu T \rightarrow f}}{dp_f}(E_\nu, p_f)$$

SK data
Interaction channels
Atm. ν flux
 ν mixings
 ν interactions

Atmospheric ν fluxes, oscillations, uncertainties

Atmospheric ν flux (Input) :

< 100 MeV: FLUKA2005

> 100 MeV: HKKM2014

Battistoni et al., Astropart.Phys. 2015

Honda et al., PRD 2015

Neutrino mixing:

3v framework + matter effect

Uncertainties:

10—100 MeV: ~25%,

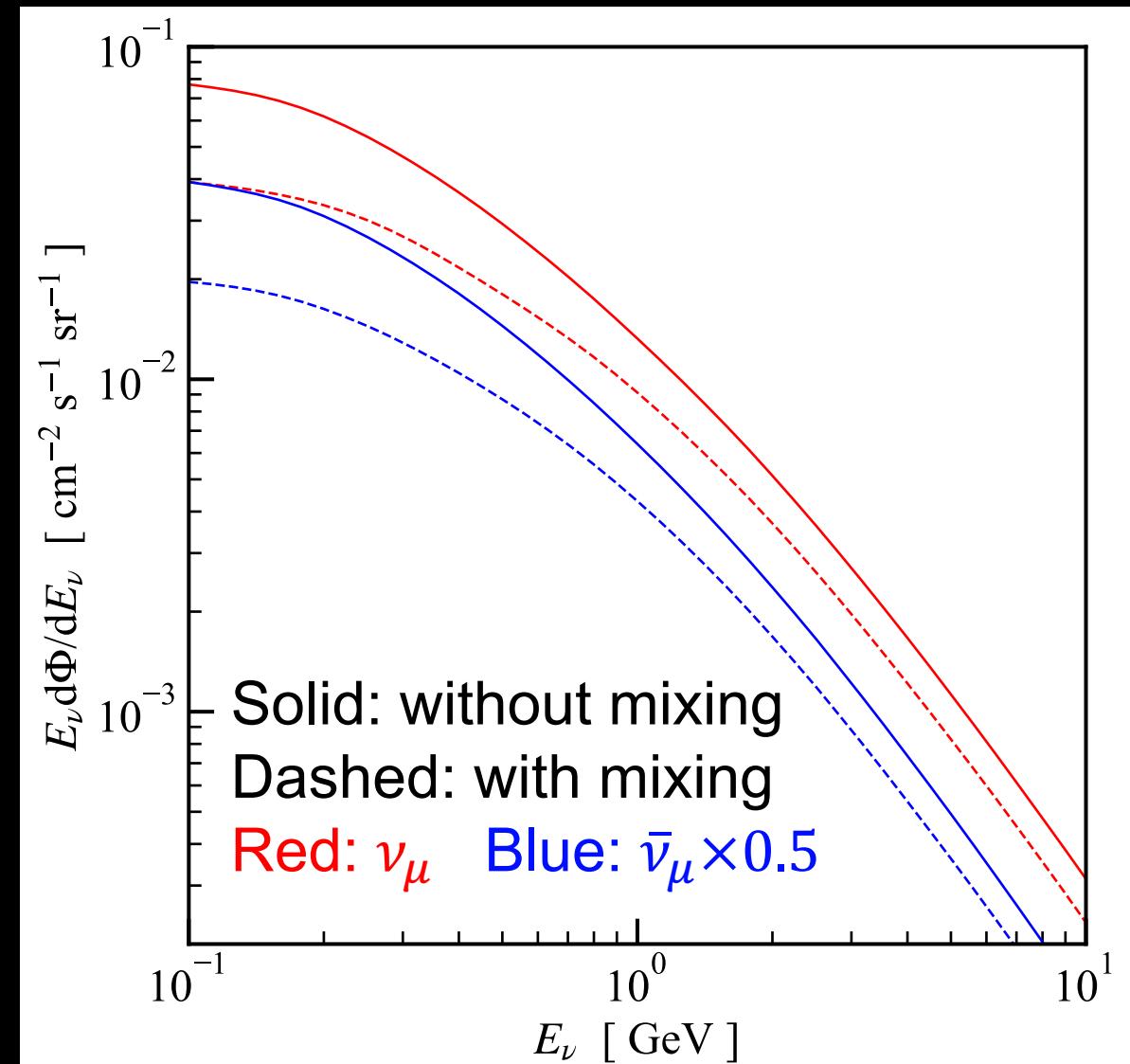
0.1—1.0 GeV: ~20%,

1.0—10 GeV: ~15%, according to refs:

Battistoni et al., Astropart.Phys. 2015

Honda et al., PRD 2007, PRD 2015

Barr et al., PRD 2006; Evans et al., PRD 2017



Atmospheric ν fluxes, oscillations, uncertainties

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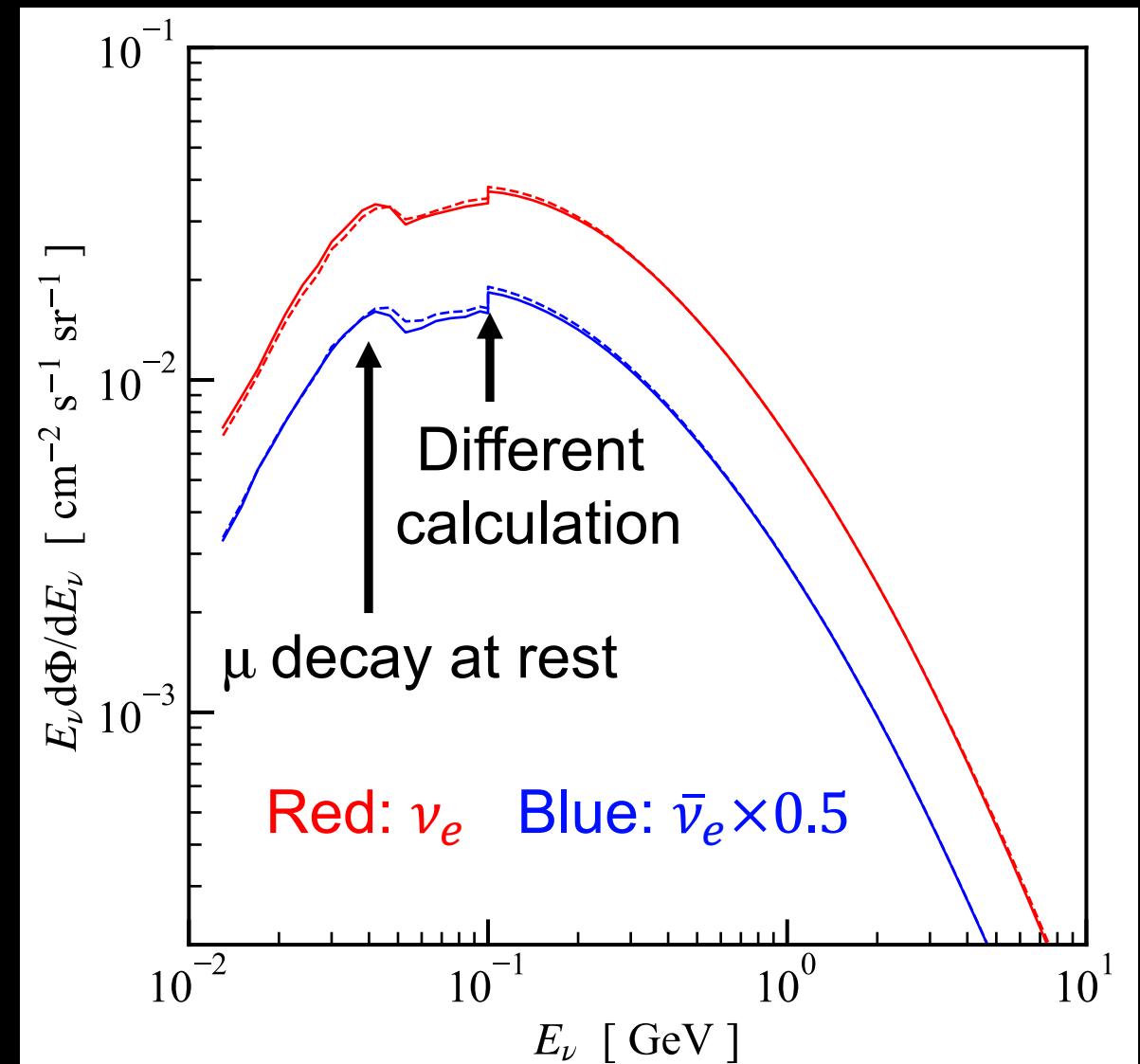
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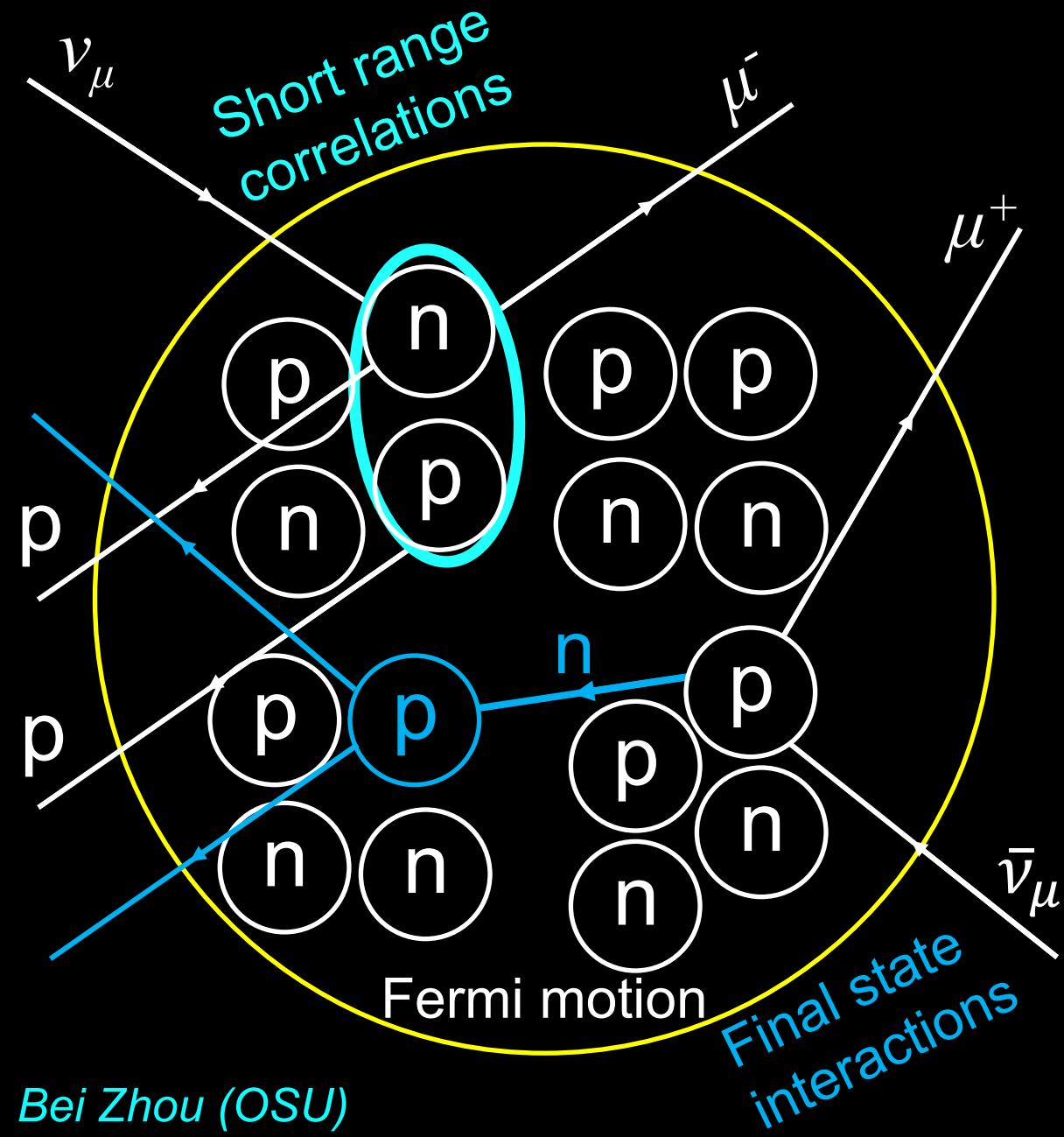
Battistoni et al., Astropart.Phys. 2015

Honda et al., PRD 2007, PRD 2015

Barr et al., PRD 2006; Evans et al., PRD 2017



Neutrino-nucleus interactions



We use GENIE v2.12.0:

Nuclear model:

1. relativistic fermi gas + SRC (default)
2. Eff. Spectral function + TEM

Other nucl. Effects: Pauli blocking, shadowing, anti-shadowing, EMC, de-excitation, etc.

Neutrino-nucleon vertices:

CCQES: Llewellyn-Smith model

RES: Rein-Sehgal model

Final-state interactions: INTRANUKE/hA model

Neutrino-nucleus interactions

Interaction types:

$\lesssim 1.0$ GeV: Quasi-elastic scattering (QES)

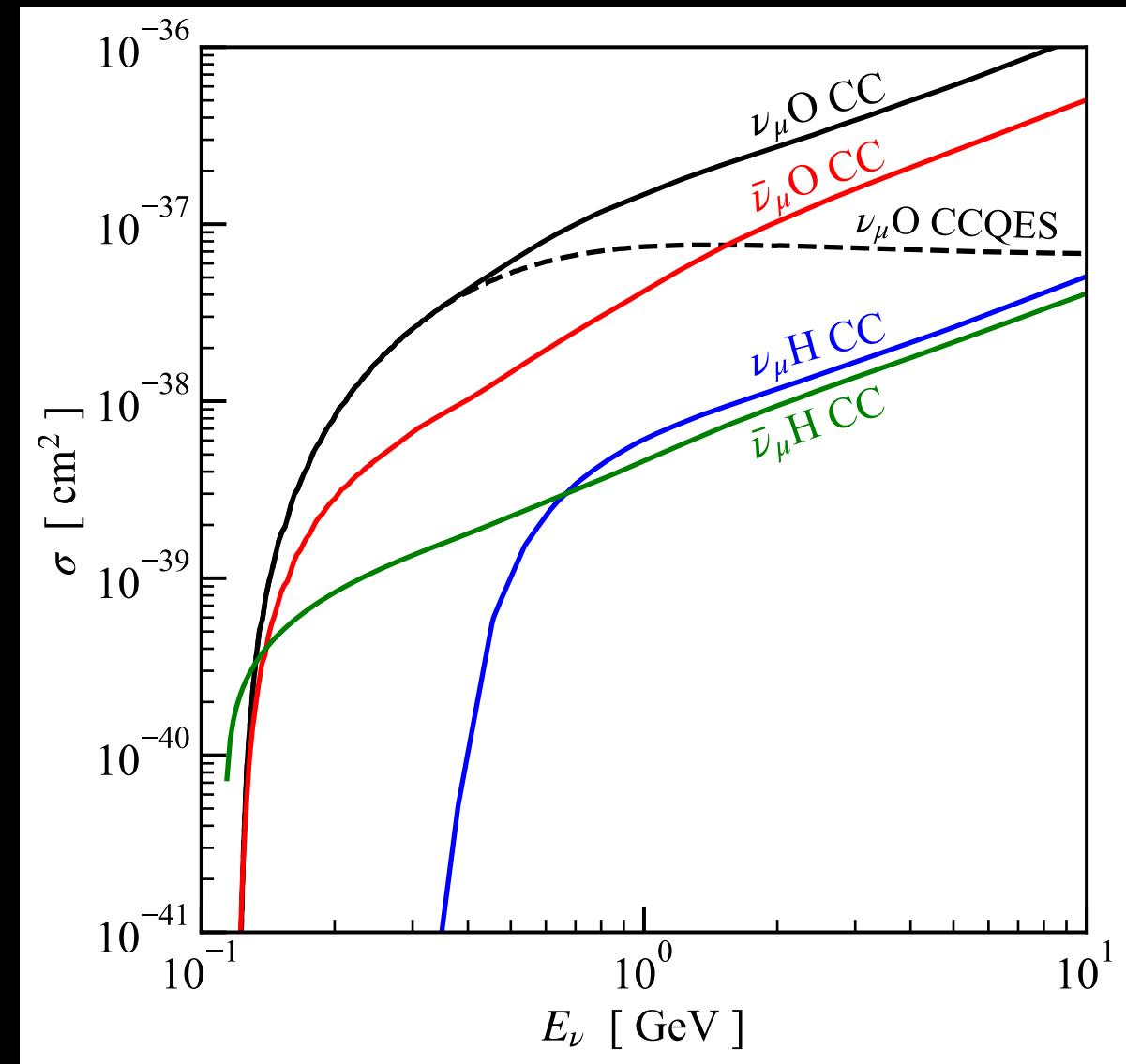
~ 1 –few GeV: Resonance productions (RES)

\gtrsim few GeV: Deep-inelastic scattering (DIS)

Uncertainties:

An overall uncertainties of $\sim 20\%$ for hundreds MeV, even larger for sub-100 MeV

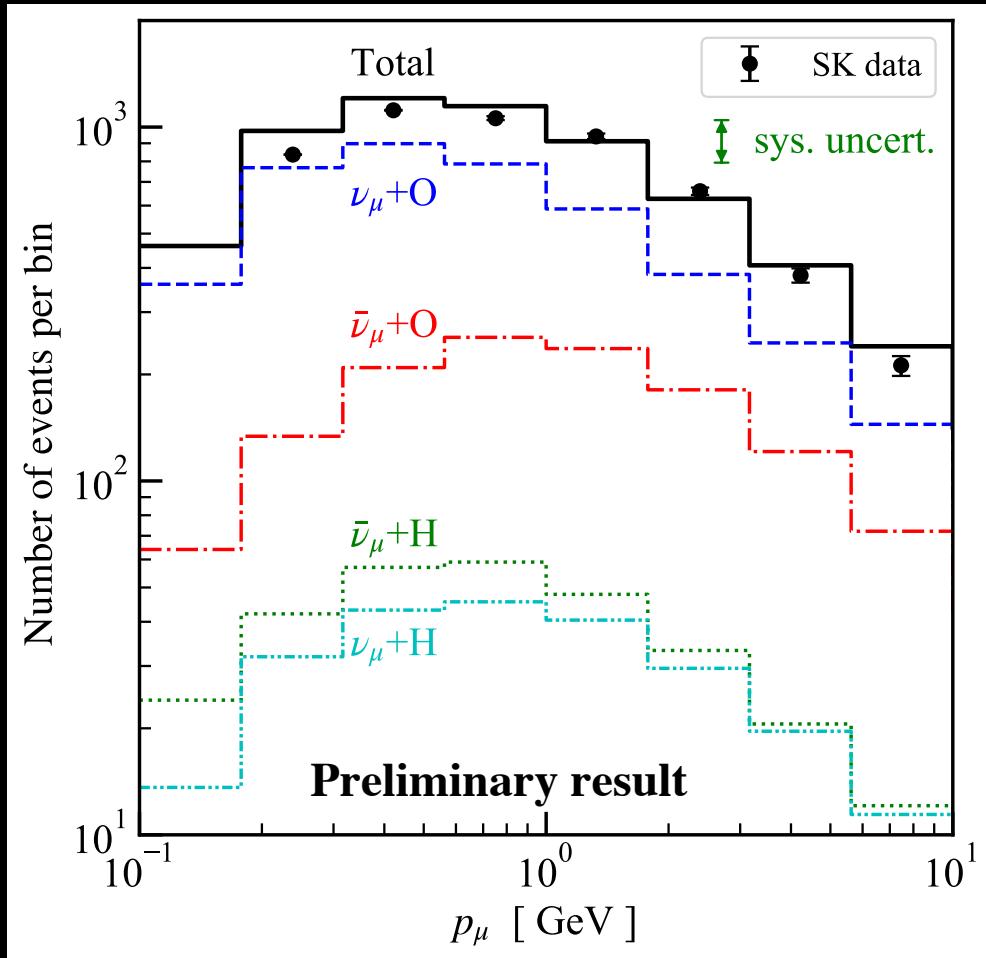
e.g.,
SNO Collaboration, ApJ 2006
Super-K Collaboration, PRD 2016



Part 1: study the underlying physics of LE atm. ν in Super-K

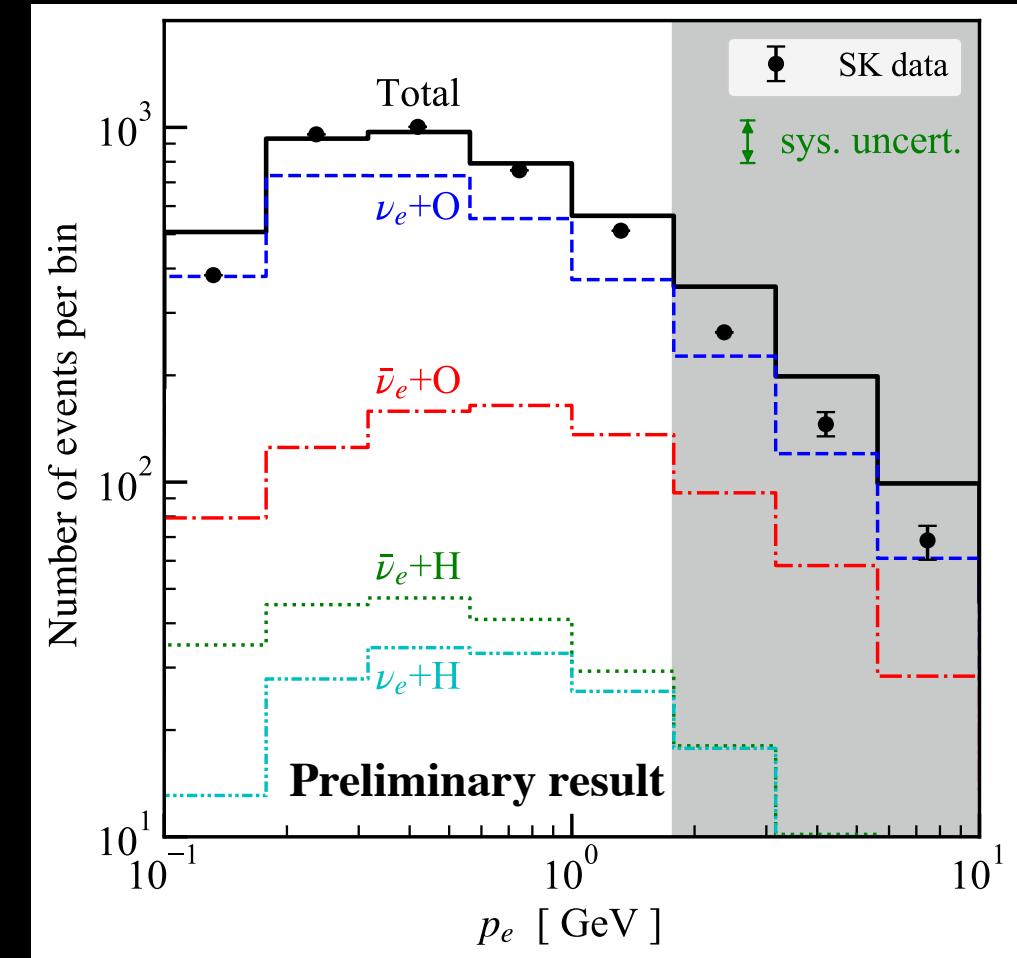
Reproduce SK high-energy atm. ν data

Reproduce SK High-Energy Atm. v Data



SK μ data: add all 3 datasets together

Calculation matches SK High-Energy data well!



SK e data

Data from SK collaboration, PRD, 2005, hep-ex/0501064

Part 1: study the underlying physics of LE atm. ν in Super-K

Reproduce SK low-energy atm. ν data

Basic Calculational framework, naïve calculation for LE

Detector exposure (~ 1500 days for SK-I)

$$\frac{dN_f}{dp_f} = \Delta t \sum_{\nu T \rightarrow f} N_T \int dE_\nu \frac{d\Phi}{dE_\nu}(E_\nu) P_{osc}(E_\nu, \theta_z) \frac{d\sigma_{\nu T \rightarrow f}}{dp_f}(E_\nu, p_f)$$

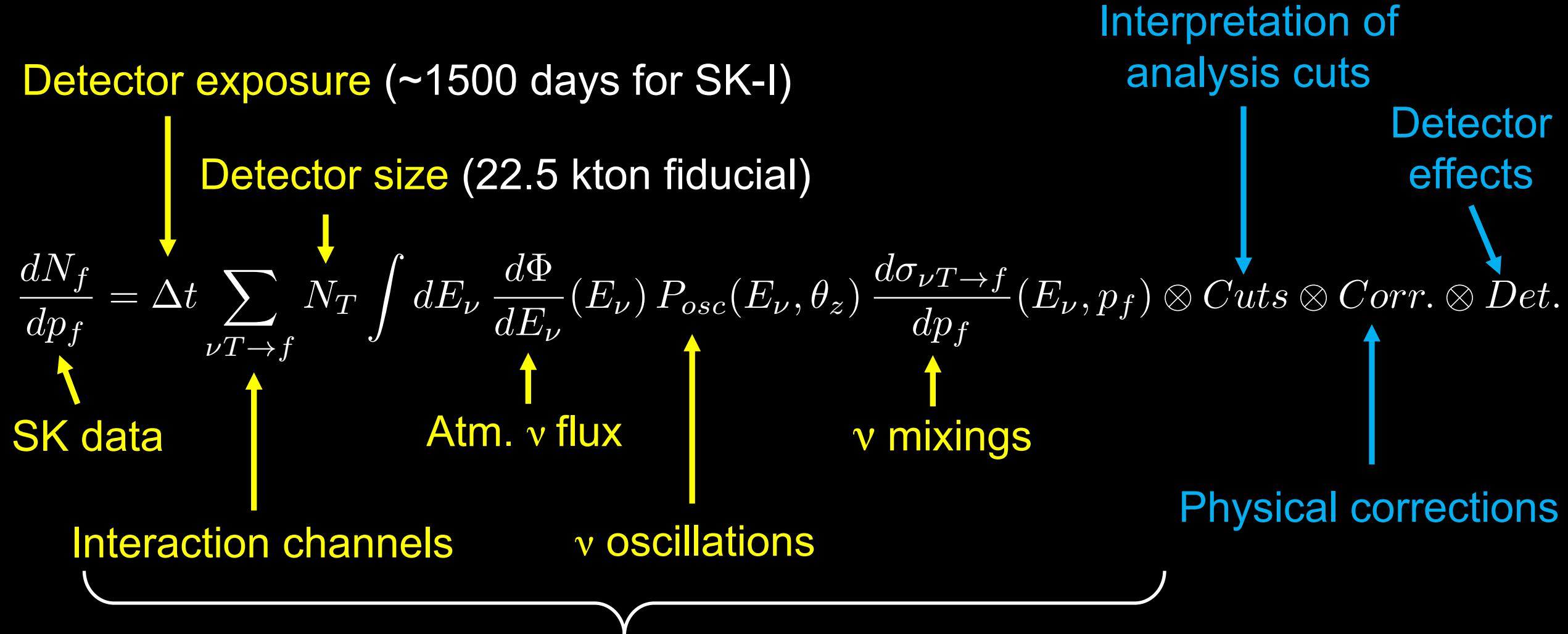
SK data
Interaction channels
Atm. ν flux
 ν mixings
 ν interactions

of invisible muons:

Detected: 146

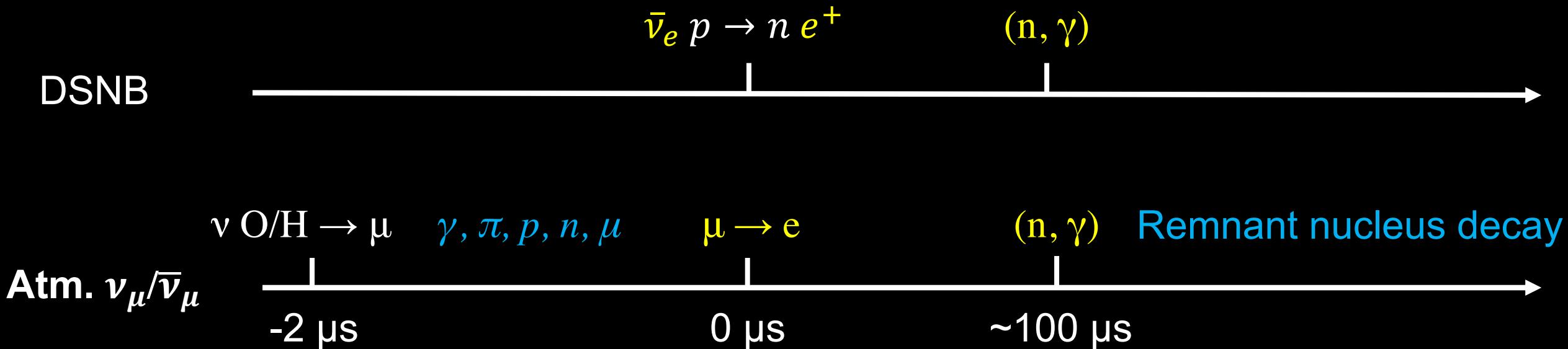
Calculated: 60% larger (RFG), 80% larger (EffSFTEM)

Full calculational framework, for LE data



Tested by reproducing high-energy data

Interpretation of analysis cuts



SK analysis cuts

- FV cut; Spallation cut; Solar cut;...
- Double peak cut, Sub-event cut...
- Pion cut; Multi-ring cut; Cherenkov angle cut; ...

Our interpretation: we throw away

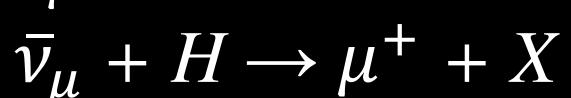
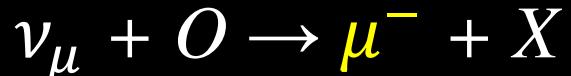
- $K_\mu > 55$ MeV (Theor. Cherenkov thres.)
- Others above Cher. Thres.
- Events with π
- Nuclear γ

Result: # of invisible μ decrease by 60%

Nuclear γ in GENIE and Super-K

- Theoretical
 - GENIE uses *Ejiri 1993* (theory) and *Kobayashi+ 2005* (experiment)
 - $BR\gamma \sim 50\%$ overall, mostly $\sim 6\text{-}8$ MeV
 - Consistent with *Ankowski+ 2012* (theory), T2K PRD 2014 (experiment).
 - However, above are for one-nucleon kick out. But for our case, multi-nucleon kick-out is very common...
- Experimental
 - SK people don't know how much they cut.

Physical correction 1: μ^- capture



Decay in bound state



Bkgd for DSNB~

Atomic capture (1s state)

μ^-

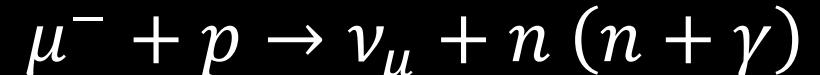
Electron cloud

O16

~79%

~21%

Nuclear capture



Won't be bkgd for DSNB~

The numbers are from
our FLUKA simulation

Physical correction 2: NCinv π^+

$\pi^+ KE < 72 \text{ MeV}$, invisible in SK

invisible $\pi^+ \rightarrow \mu^+ \rightarrow e^+$, background for DSNB

Increase invisible muon # by $\sim 25\%$

1. $\nu_x + p \text{ (O or H)} \rightarrow \nu_x + n + \Delta^+$ (NC RES, dominant)

$\Delta^+ \rightarrow n + \pi^+$

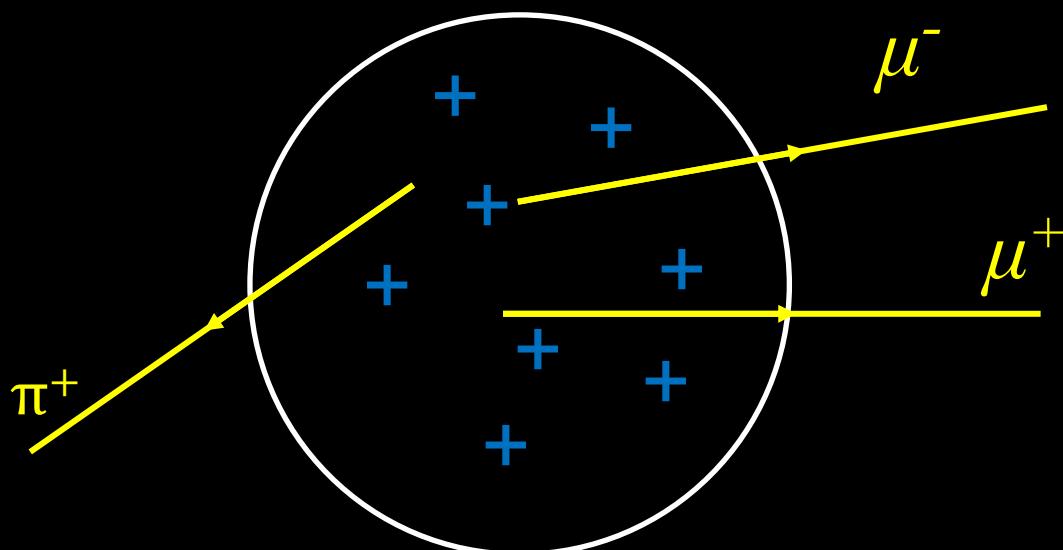
2. $\nu_x + p/n \text{ (O or H)} \rightarrow \nu_x + \pi^+ (+ p) \text{ (NCQES + FSI)}$

NC π^0 and π^- are irrelevant

π^0 decay to two γ 's

π^- mostly 1) atomic capture 2) $\sim 100\%$ nucl. capture, $\pi^- + O \rightarrow p's, n's, \gamma's$

Physical correction 3: Coulomb distortion



Physical effects:

Increase (decrease) momentum for + (-) charged particle:

- 1) Distort the $d\sigma/dp$
- 2) Decrease (increase) overlap with nuclear wavefunction, hence σ

We use:
Modified eff. moment. approx. (MEMA).
(Engel, PRC
1998)

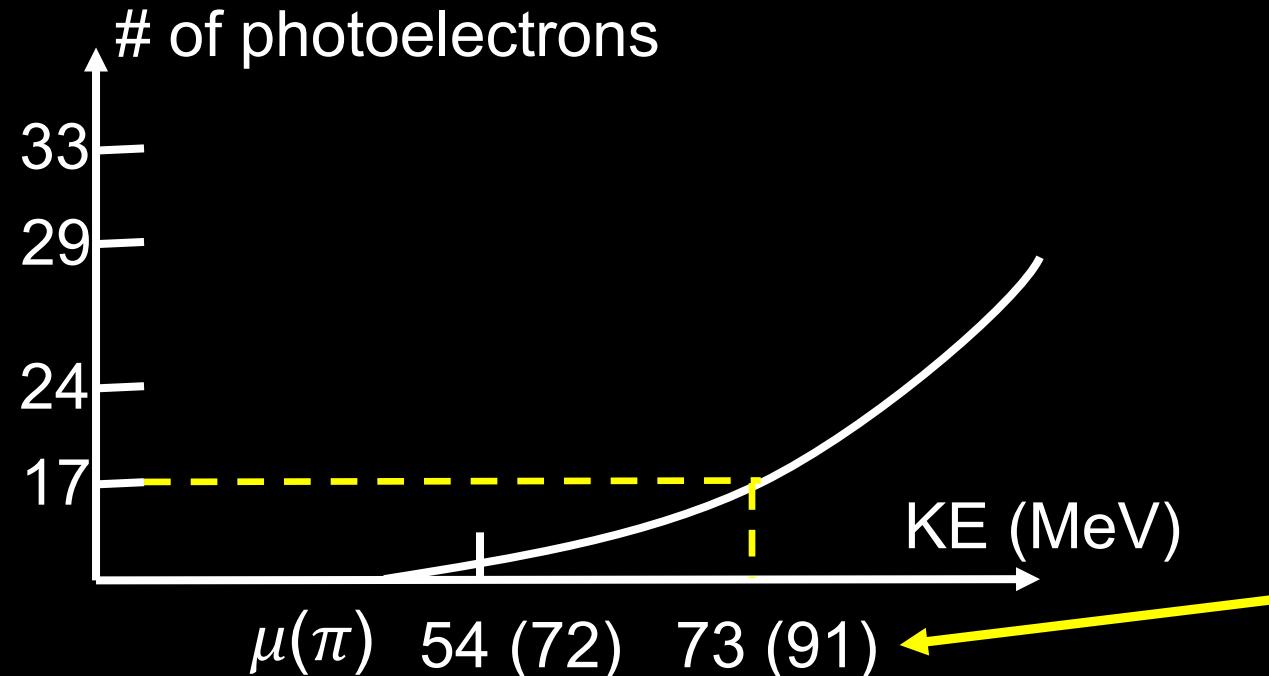
$$V_{electrostatic} = \frac{3Z\alpha}{2R_A}$$

- 1) Induce a shift of the total energy
- 2) Rescale scattering amplitude

Results of invisible muon #:

For μ^+ channels, decrease 25%
For μ^- channels, increase 25%
Net effect: increases by 15%.

Detector-effect correction: Cherenkov threshold



Theoretical Cherenkov threshold:
 β (particle speed) > $1/n$ (photon speed)

n , refractive index

Bei Zhou (OSU)

However, detector has trigger threshold
→ Real Cherenkov threshold higher.

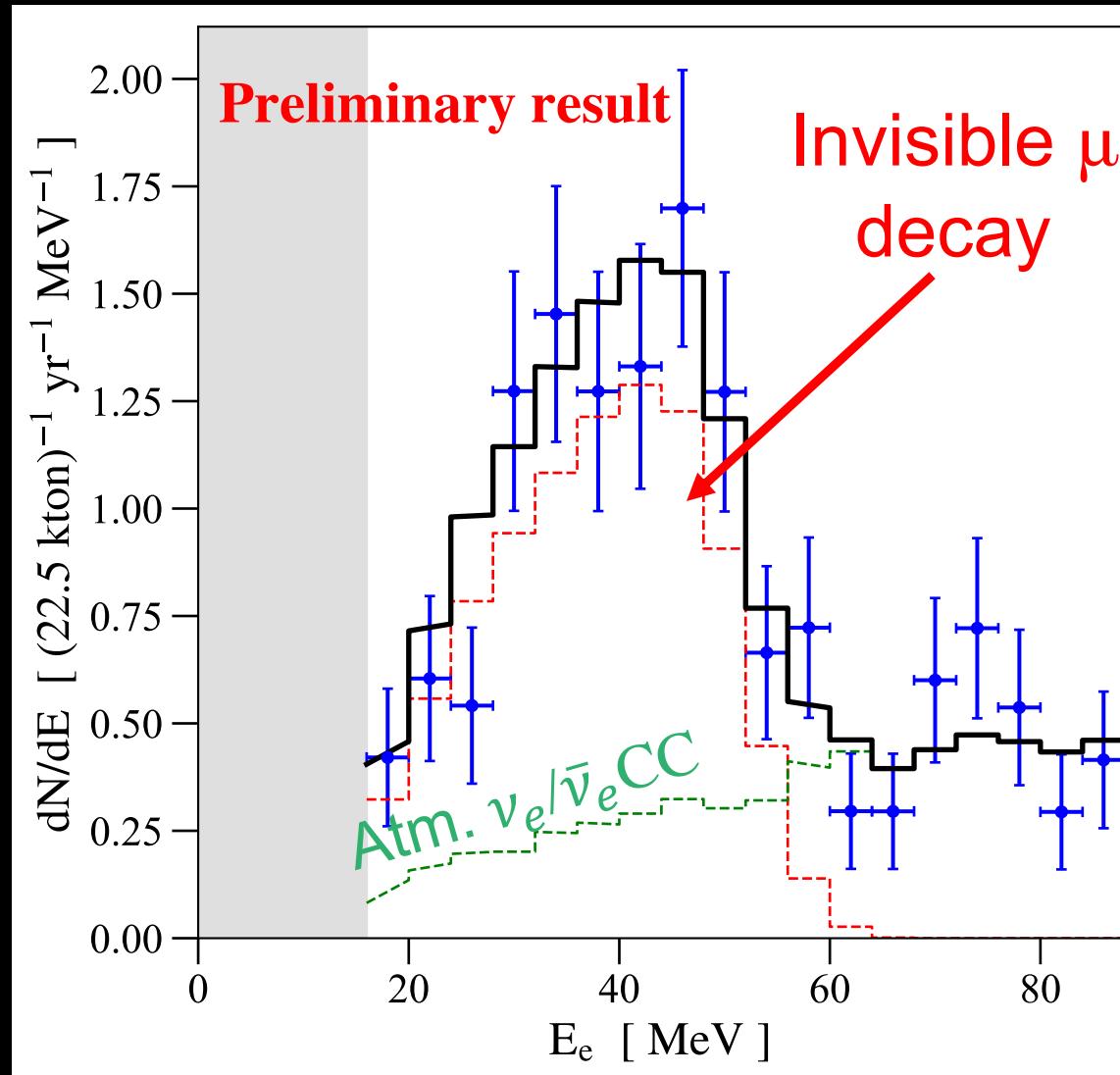
We

- Chose 17 p.e. as the threshold.
- $\Rightarrow \approx 340$ Cherenkov photons
- $\Rightarrow \approx 73$ MeV for μ and ≈ 91 MeV for π

(Consistent with SK's detector simulations
by Chenyuan Xu from SK collaboration)

Increase # of invisible μ by: 35%.

First Reproduce SK Low-Energy Atm. v Data



$\left\{ \begin{array}{l} 80\% \text{ Atm. } \nu_\mu/\bar{\nu}_\mu \text{ CC} \\ 20\% \text{ Atm. } \nu_\chi \text{ NCinv}\pi^+ \end{array} \right.$

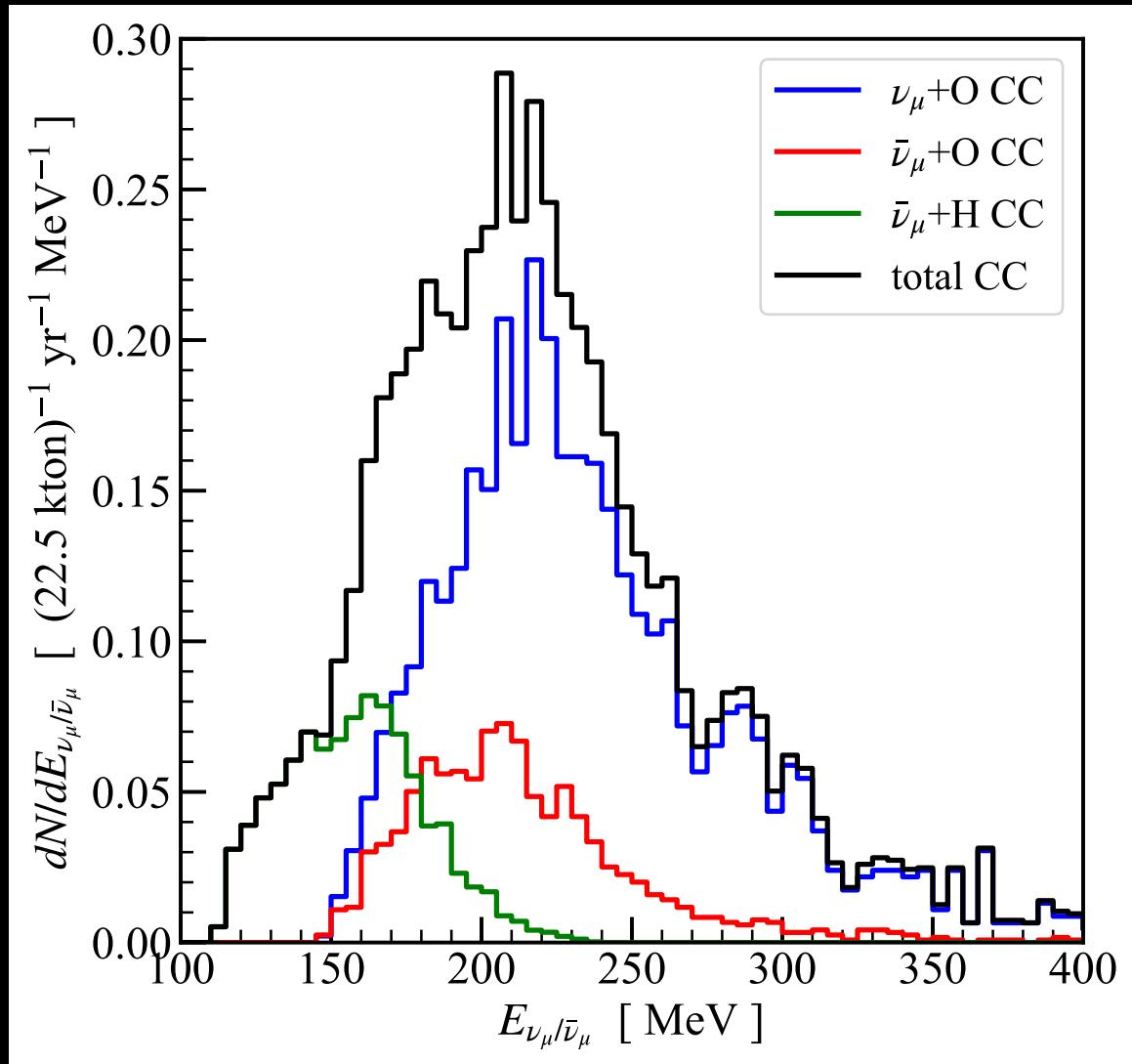
EffSSTEM model:
~10%--~20% higher than
Rel. Fermi Gas + SRC

BZ, John Beacom, *in prep*, (2019)

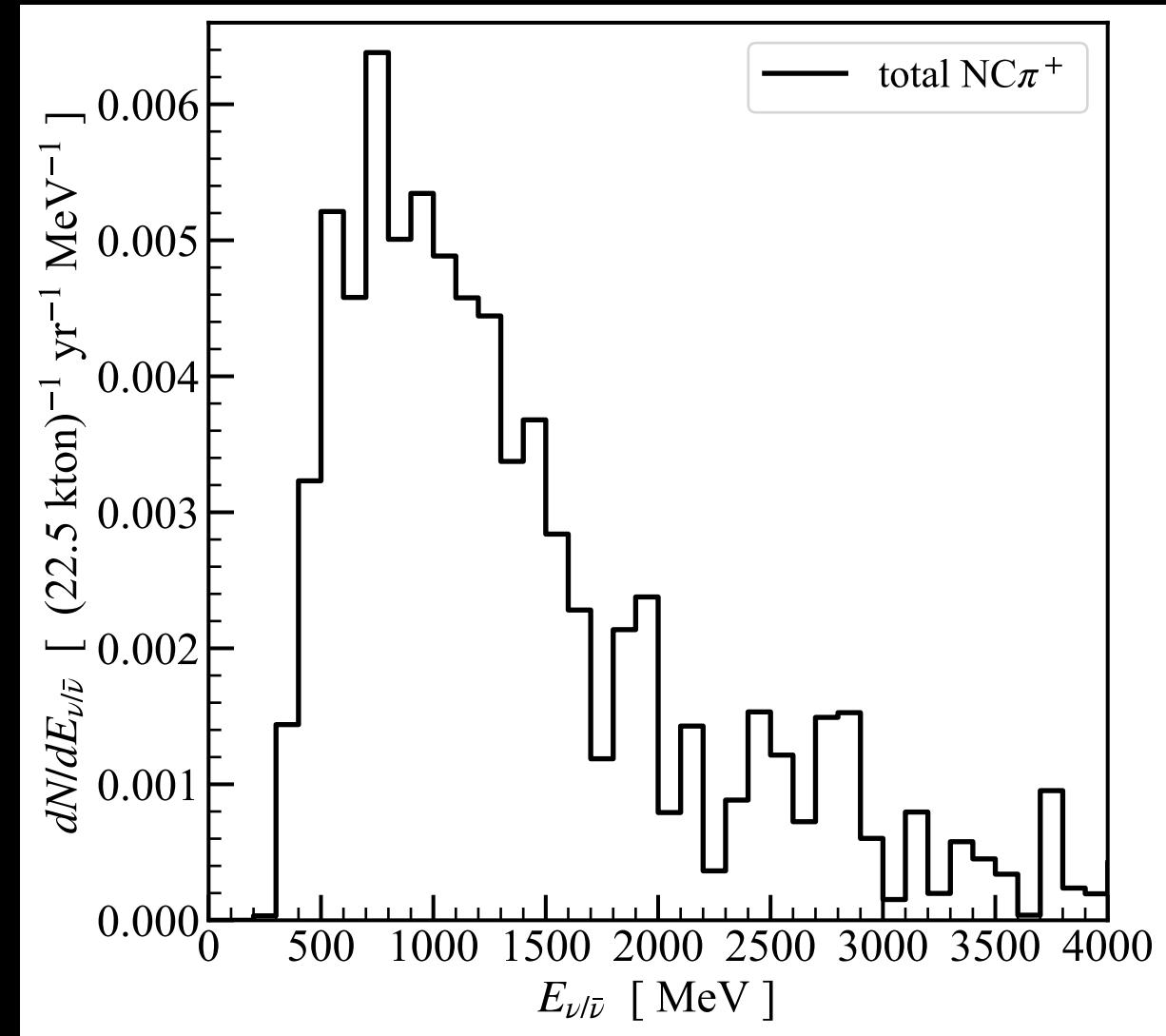
Data from SK collaboration, PRD, 2012, arXiv:1111.5031

Calculation matches SK Low-Energy data well!

SK low-energy data: source neutrino spectrum



Atm. $\nu_\mu/\bar{\nu}_\mu \text{CC}$

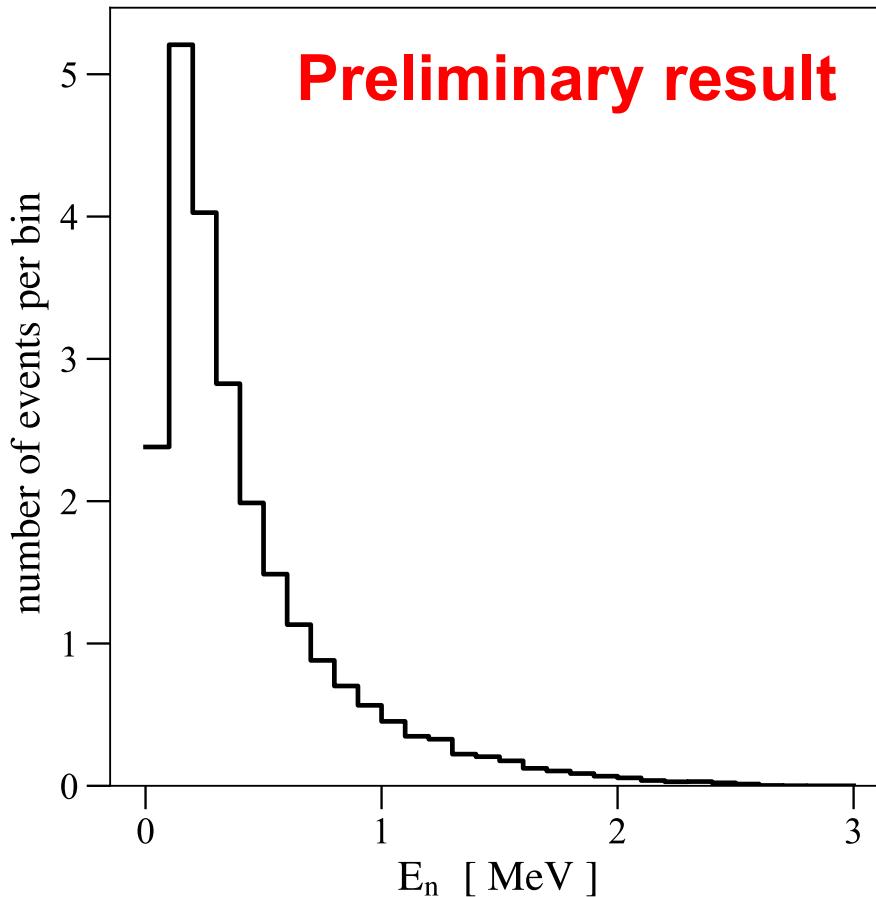


Atm. $\nu_x \text{ NCinv}\pi^+, 20\%$

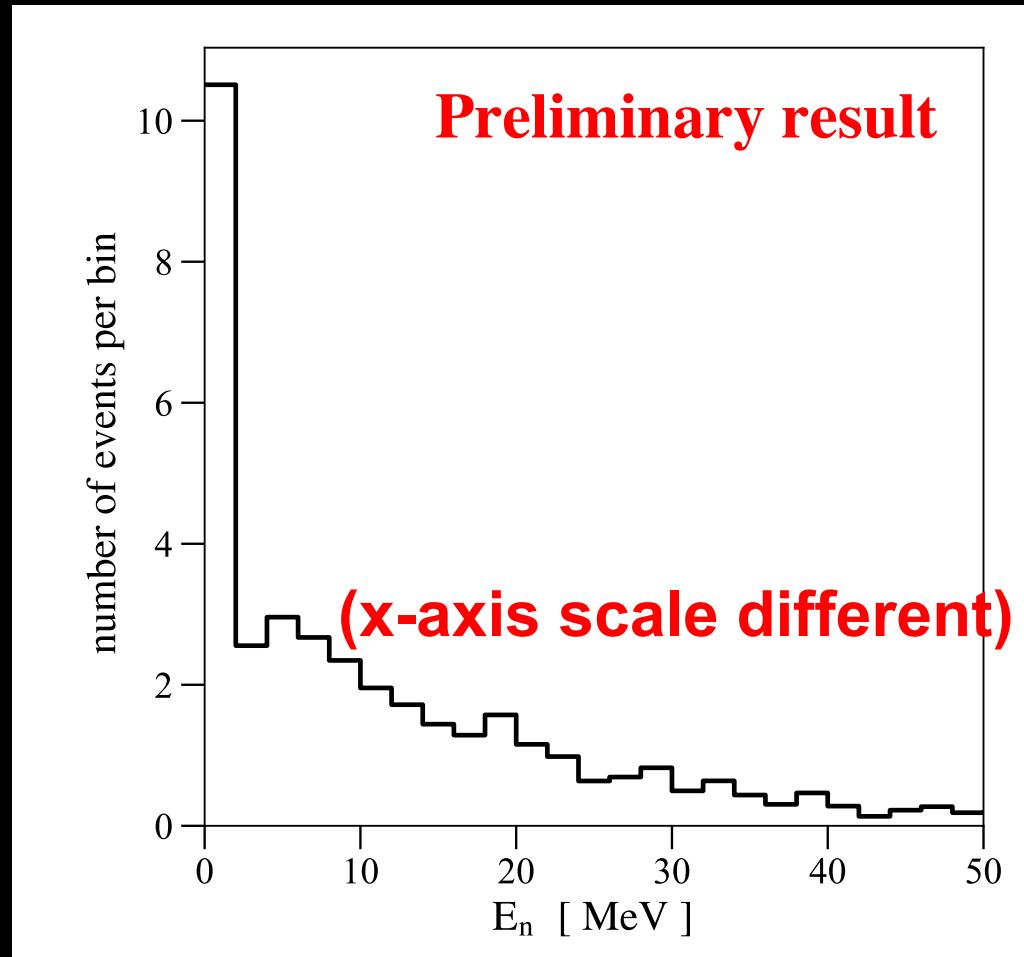
The physics has been understood well.

Then Part 2: How to reproduce the backgrounds?

One Major Clue: Neutron Energies



DSNB signals



Atm. $\nu_\mu(\bar{\nu}_\mu)$ backgrounds

So neutrons from atm. v bkgd can propagate much further!

More about neutron propagation in water

Physical mechanism (major)

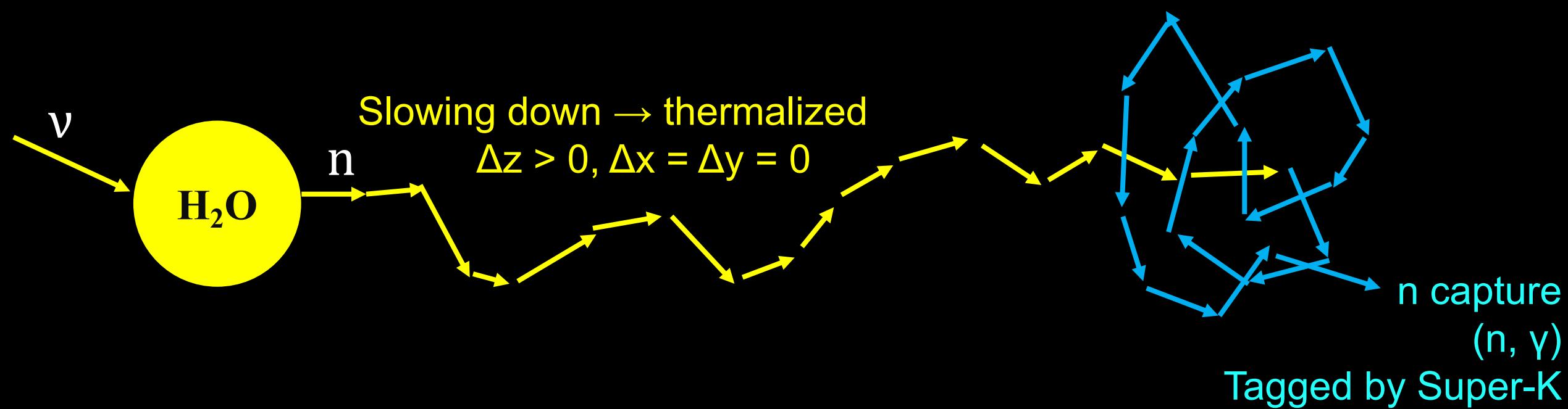
- Elastic on O:
 ΔE negligible, direction changes lot
- Elastic on p:
 $\Delta E \sim 1/2 E$, direction changes little

Physical mechanism (minor)

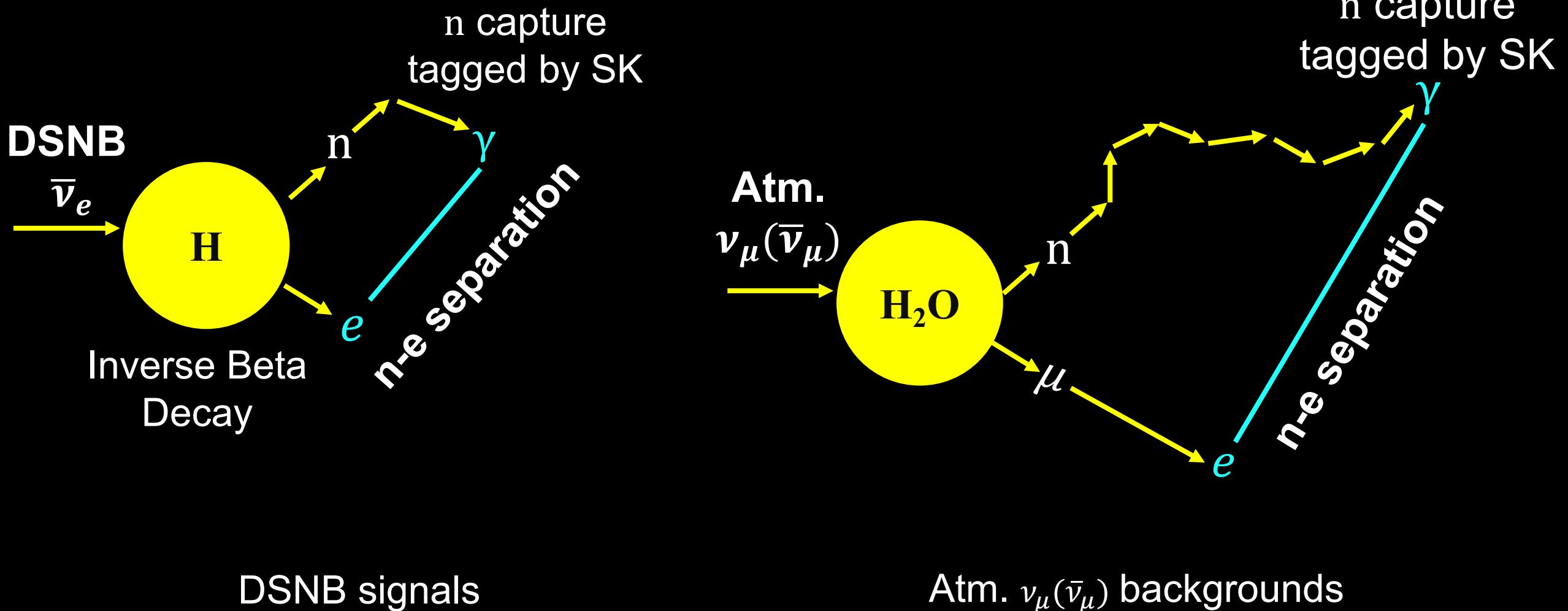
- $> \sim 1$ MeV inelastic on O
- < 1 eV, chemical bounding

Diffusing (random walk)

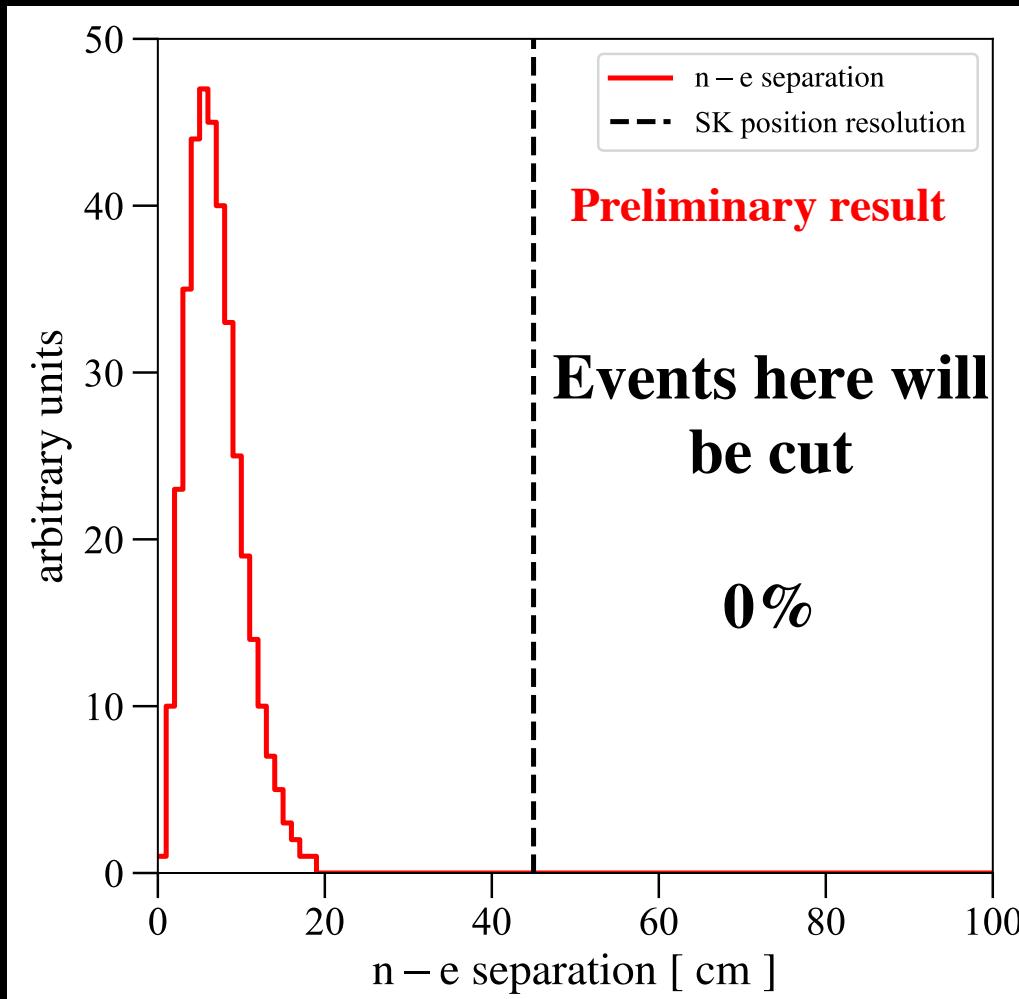
$$\Delta z = \Delta x = \Delta y = 0$$



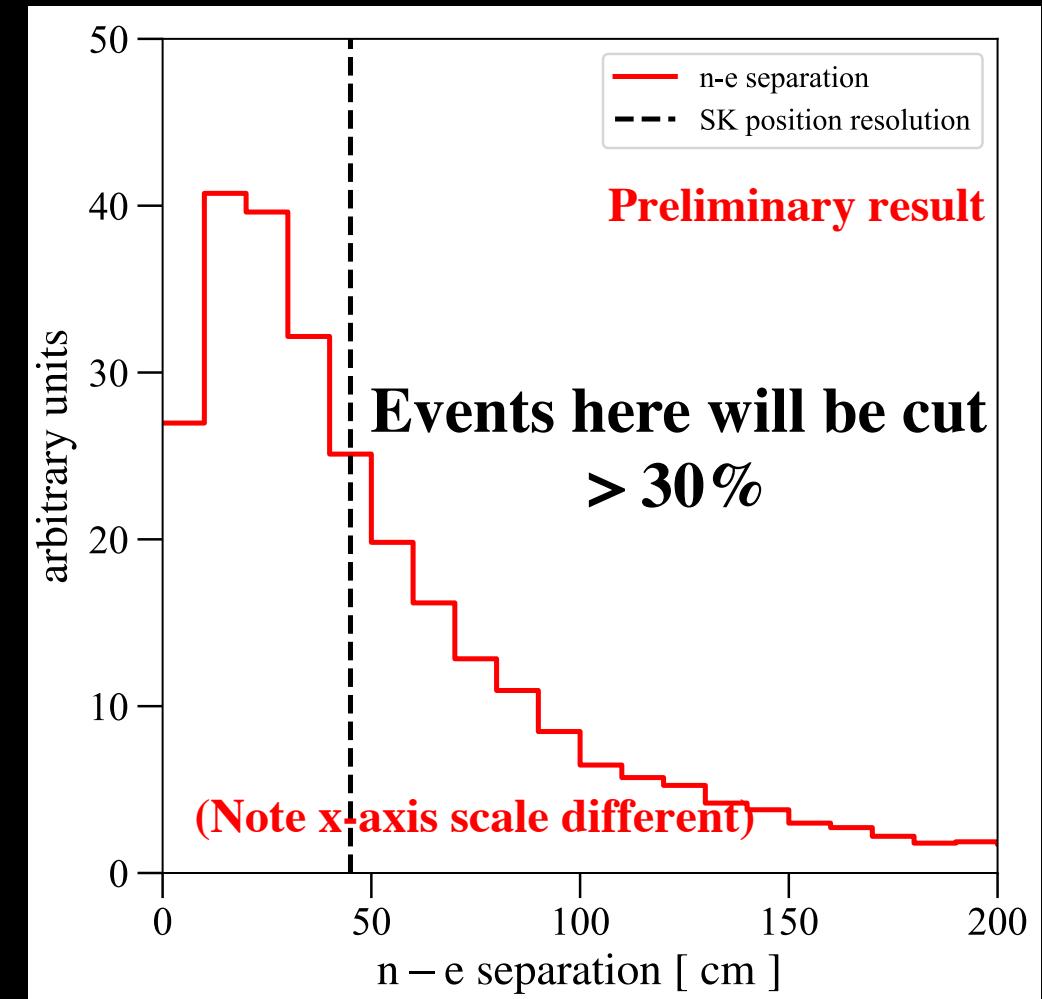
n-e separation: Definition



n-e separation distributions

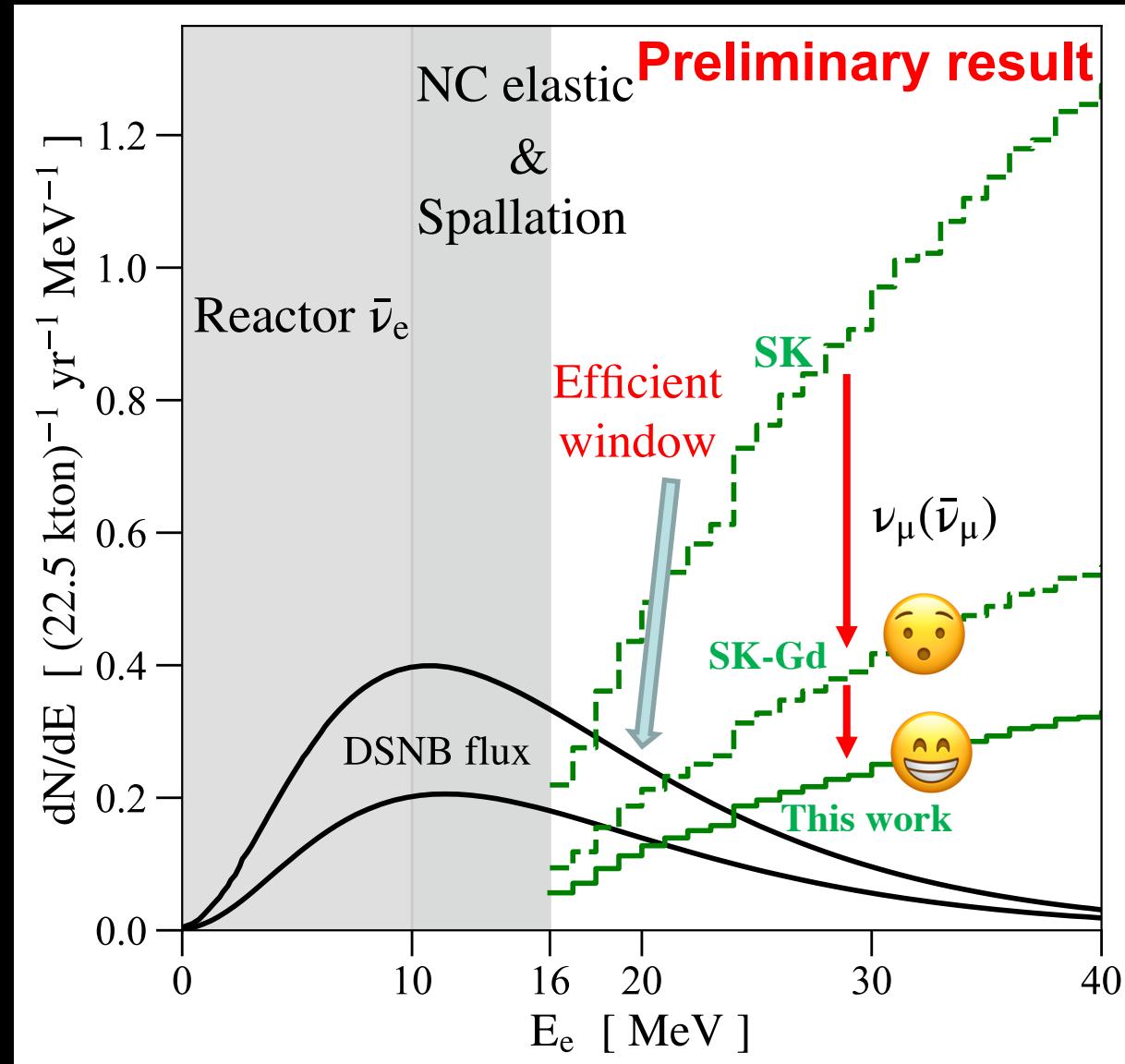


DSNB signals



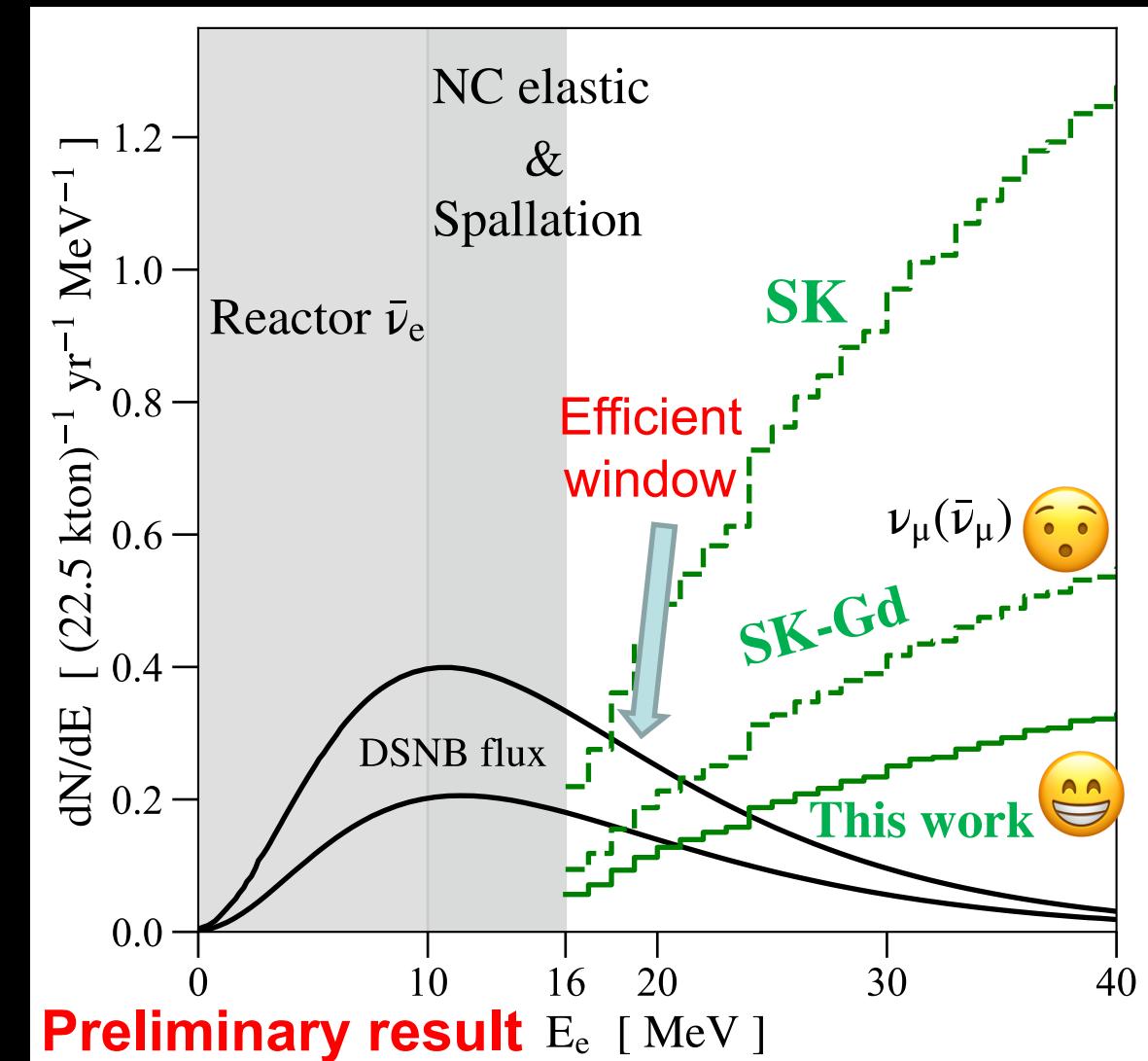
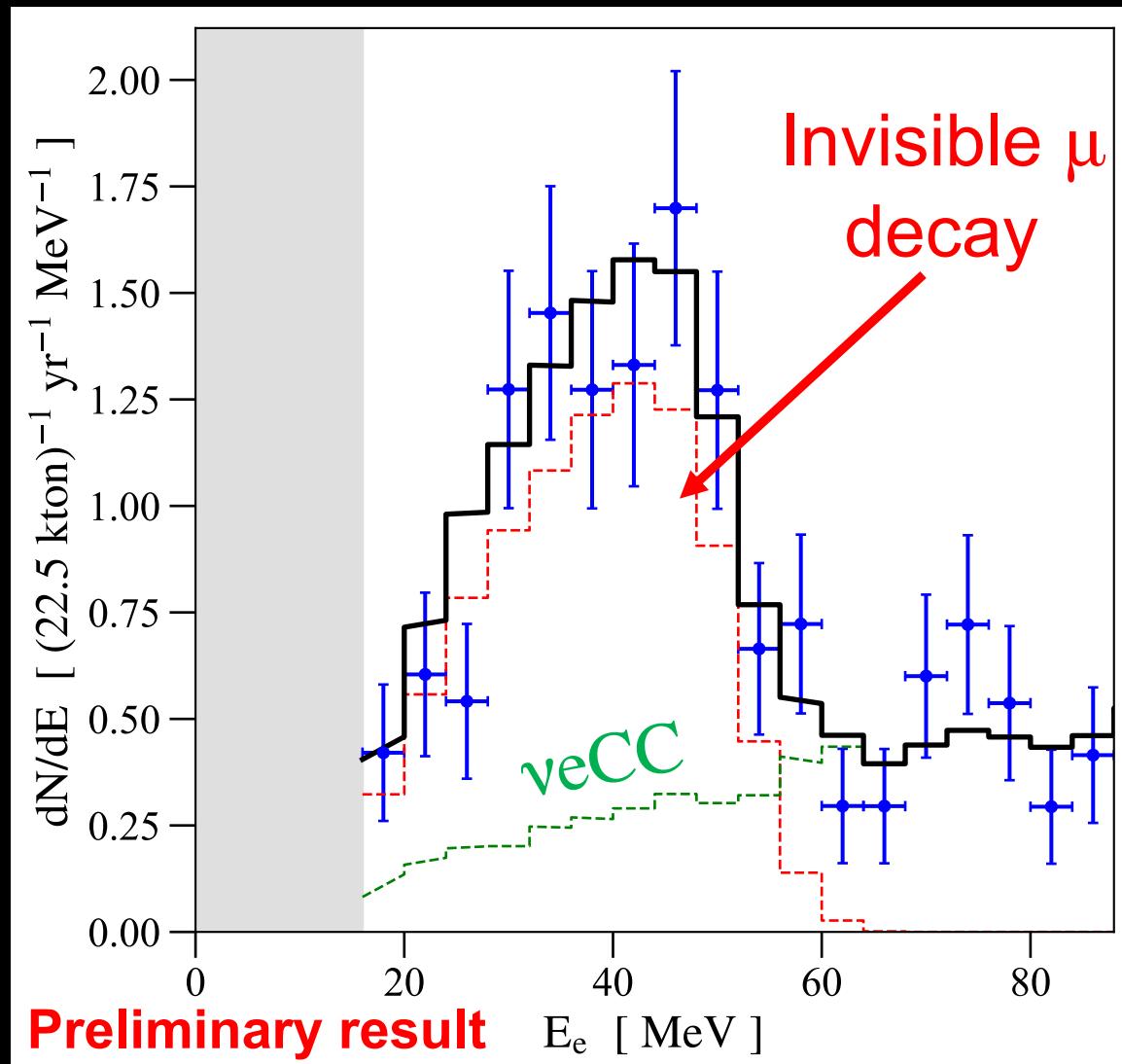
Atm. $\nu_\mu(\bar{\nu}_\mu)$ background

After our n-e separation cuts



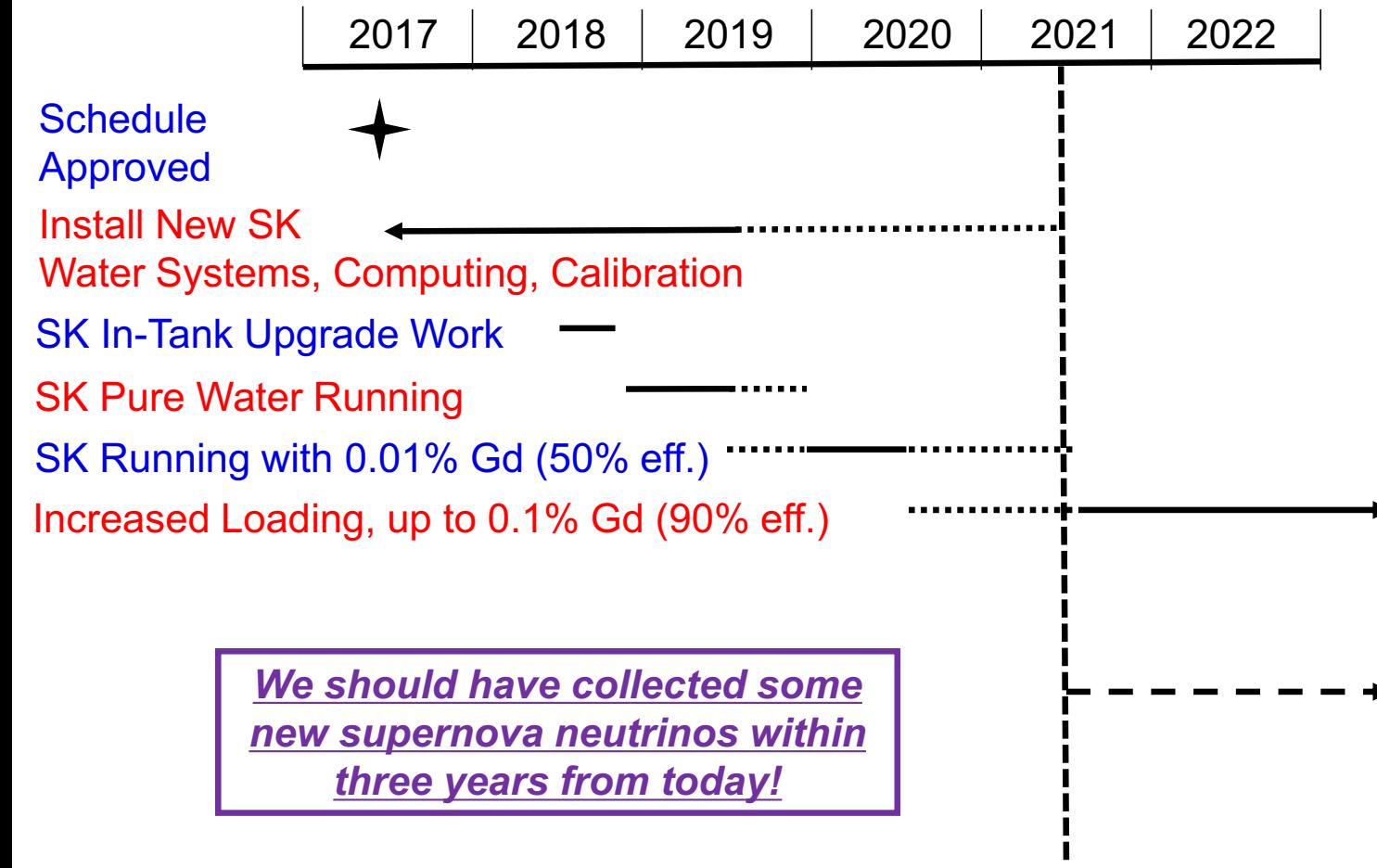
More suggested methods in the coming paper

Conclusion



Thanks for your attention!

Expected timeline for SK-Gd



*Slides from Mark Vagins of SK collaboration, (May 29, 2018)
3th Conference on the Intersections of Particle and Nuclear Physics*

GADZOOKS! SK → SK-Gd with n-tagging

- Add 0.1% Gd (Gadolinium) to SK
SK-Gd begins in late 2018.
- SK: LE n's captured on H, produce 2.2 MeV γ , hard to detect
SK-Gd: 90% LE n's captured on Gd, produce 8.0 MeV γ , easy to detect
- DSNB $\bar{\nu}_e$ always give one n
Atm. bkgd, $\simeq 55\%$ give no n or multiple n.
→ Mostly killed by n-tagging

